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Development of the JET Ion Cyclotron Resonance Frequency Heating System in Support of ITER

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ABSTRACT.
Three new improvements have recently been made to the JET Ion Cyclotron Resonance Frequency (ICRF) antennae to increase coupled power density and to match through rapid coupling variations during Edge Localised Modes (ELM's); both of which are key developments for the future design of the ITER ICRF antenna. Firstly, 3dB couplers were fitted to two antennae in 2004/5. Secondly, an Externally-mounted Conjugate-T (ECT) system has been installed on two antennae during 2007. Thirdly, a major new ITER-Like Antenna (ILA) was installed during 2007 to couple an ITER-relevant power density using a close-packed array of straps, with ELM tolerance incorporated using an internal (in-vacuum) conjugate-T junction with each strap fed through in vessel matching capacitors from a common vacuum transmission line. The results achieved to date on all three systems and the implications for the ITER antenna design are discussed.

1. INTRODUCTION

ITER will require the following from its ICRF system: (a) coupling and matching at power densities of approximately 8MW/m^2; (b) powering through fast (sub-ms range) changes in loading during ELM's; (c) operation at high power for long pulse lengths; (d) resilience to disruption forces; and (e) protection against arcing. These issues are strongly inter-related; for instance, the need to achieve high power density implies a dense packing of radiating straps, which increases cross-coupling between straps, thus complicating both the engineering design and the matching algorithm. JET is in a unique position to provide ITER-relevant experimental tests and information regarding all of these issues, apart from the long pulse operation. The size of plasma; the variety of ELM's; the range of plasma scenarios and diagnostics; and the variety of ICRF systems make JET ideal for assessing such inter-related RF and mechanical issues.

From 1994 to 2007, the JET ICRF system comprised four "A2" antennae (A, B, C, D), each consisting of 4 toroidally-adjacent straps [1]. The average power density coupled by these antennae (<1.5MW/m^2 in L-mode plasmas) drops by approximately two thirds during ELM's, due to load changes causing excessive power reflections on the transmission lines which trip the generator protection systems. Three new improvements, shown schematically in Figure 1, have recently been implemented to the JET system in an integrated strategy to increase power density and to develop "ELM-tolerant" matching systems. 3dB couplers have been installed to feed antennae A and B; an external conjugate-T system allows (optional) conjugate-T feeding of antennae C and D; and a major new antenna, the ILA, has become operational in 2008. Each system is discussed below.

2. ELM TOLERANCE ON JET USING 3DB COUPLERS

Hybrid 3dB couplers, under consideration for ITER [2], can divert the reflected power away from the generators to a load, as first proven on ASDEX-Upgrade [3]. Tests on JET in 2006/7 with 3dB couplers installed between antenna A and B [4],[5] confirmed their ELM tolerant properties for ICRF coupled power levels up to 1.5MW per antenna (Figure 2 shows power maintained through

ELM's on antennae A and B, whilst antennae C and D trip repeatedly), but led to observations that some arcing might not be detected by standard methods. The key issue (common to all ELM-tolerant antennae) arises from the Voltage Standing Wave Ratio (VSWR) allowed on the Transmission Line (TL) between the antennas and the 3dB couplers. VSWR-initiated arc detection systems require low tolerated VSWR values; ELM tolerant operations need an increase in the allowed VSWR values in order for the reflected power during ELM's to reach the 3dB load. These conflicting requirements mean that the generator switch-off following an arc could be delayed. Furthermore, during the test performed, events undetected by the VSWR arc protection were identified as arcs at voltage nodes in the vacuum TL [6]. These observations led to an upgrade of the VSWR arc protection with restrictions at operating frequencies where voltage nodes might occur at susceptible positions. To date, the ELM tolerance properties of the 3dB-coupled system have allowed up to 1.75MW per antennae to be coupled at 47MHz without tripping during type I ELM's.

3. THE JET EXTERNAL CONJUGATE-T (ECT) SYSTEM

During 2003, a prototype Externally-mounted Conjugate-T (ECT) system was installed between one pair of adjacent straps of antenna C. This brief test proved highly successful [6] and has led to the installation of full ECT junctions, plus a dedicated arc detection system (Advanced Wave Amplitude Comparison System [7]), between antennae C and D during the 2006/07 shutdown. This system pairs one strap from each antenna together in the conjugate-T configuration, and so does not utilise a close-packed antenna array.

Figure 3 shows JET Pulse No: 74530 in which antennae C and D were both powered through ELM's at a generator power level of 0.25MW/antenna using a conjugate-T impedance of $Z_t = 4-1.5j\Omega$. This confirms both the capability of the external conjugate-T configuration to remain matched during a transition to H-mode, and the ELM-tolerance of this system. In addition, this initial operation confirmed that matching using network analyser measurements prior to vacuum matching can result in a robust match. At present, this configuration is limited to low power testing; operation at significant power levels requires successful commissioning of the arc detection system.

4. THE ITER-LIKE ANTENNA (ILA)

Over the last seven years, a major project has been undertaken by EU associations and EFDA JET CSU to provide an additional JET antenna. The ILA shown in Figure 4 is intended to couple 7.2MW across the frequency range 30-55MHz, using a close-packed array of straps mounted as four Resonant Double Loops (RDL's), each consisting of two poloidally adjacent straps, arranged in a 2 toroidal by 2 poloidal array [8]. ELM tolerance is incorporated using an internal conjugate-T junction with each strap fed through invessel matching capacitors from a common vacuum transmission line, as shown in Figure 5.

The design of the ILA required many RF and mechanical challenges to be overcome; many of them inter-related. The 7.2MW ILA specification corresponds to the $8MW/m^2$ required for ITER, and the complexity of the matching system matches that of the ITER antenna, which also incorporates four RDL's [2]. Note that decouplers, proposed for the ITER ICRF system, cannot be fitted on an internally-matched conjugate-T antenna such as the ILA.

During the ILA design phase it was realised that conjugate-T configurations are at risk of damage from arcing in low impedance sections of the antenna (close to the T-point shown in Figure 5), which result in undetectable VSWR changes. It has proved necessary, therefore, to both develop a novel Scattering Matrix Arc Detection system (SMAD) [9] and to incorporate a Sub-Harmonic Arc Detection system (SHAD) developed on ASDEX-Upgrade [10] and Tore Supra [11]. The mechanical engineering design challenges posed by the ILA were significant given: the substantial disruption forces on JET; the thermal demands set by the 10s operating pulse length; and the requirement that the in-vessel capacitors be positioned to an accuracy of ±25mm in a stroke of 52mm. All of these design objectives were achieved successfully; in particular, the antenna has now been subjected to a 4MA 495 Tonne JET disruption, without apparent problems.

4.1. COMMISSIONING OF THE ILA ON THE JET RF TEST BED

Prior to installation, the four RDL's were tested without major issues up to RF voltages of 42kV (out of the maximum design voltage of 45kV) for 5 seconds every 10 minutes by vacuum matching at the central operating frequency of 42MHz. About 250kW per RDL was required to reach this voltage and about 1MJ was dissipated in the RDL (Figure 6); note that RDL34 is the lower left as observed from outside the antenna looking towards the plasma (RDL12 is the upper left; RDL56 is upper right and RDL78 is the lower right). Low power matching studies allowed the development of matching algorithms on single RDL's, paired RDL's and finally for the full array (Figure 7) when loaded by a salt water load at various frequencies and various conjugate T-point impedances (3-6Ω). The results showed that the capacitors can track to the required match in a few seconds, despite significant offsets in the starting positions. This timing was subsequently reduced by adjusting the matching algorithm parameters.

4.2. FIRST OPERATION OF THE ILA ON JET

The ILA was installed onto JET Octant 2 during August 2007 (using remote handling to manipulate the 260kg housing), with first operation on plasma on 6th May 2008. Subsequent commissioning has concentrated on the key issues of: matching on varying plasma loads; maximising coupled power; demonstrating ELM tolerance; validating the frequency range; and testing arc protection.

A key design choice for an antenna based upon a close packed strap array is the depth of the vertical septa running between, and parallel to, adjacent straps. Moving the septum edge forward relative to the straps lowers the mutual coupling between straps, which simplifies matching, but decreases the coupled power. A recent test on Tore Supra [12] validated the matching of antenna in the conjugate-T configuration, with the septa deepened to facilitate matching, at the expense of coupled power. Following modelling of the ILA using MicroWave Studio [13], the ILA design team adopted shallower septa, and so the first key issue for the ILA was the capability to match. Matching has now been achieved at 42MHz and 33MHz in L-mode and H-mode plasmas, with ROG (distance between the separatrix and the JET mid-plane limiter position) between 4 and 7cm (corresponding to order 13-16cm between the separatrix and straps). Figure 8 shows matching of half the antenna array in Pulse No: 73587 in which the ROG was increased by 3cm in four steps (a), with the coupled power (b) and conjugate-T impedance (c) held constant. As the antenna moves away from the plasma, the coupling resistance (d) drops appreciably, the strap voltages (e) rise, and capacitor settings vary to maintain matching (f). The conclusion is that the antenna remains matched throughout a pulse in which slow variations in load are deliberately introduced. Unfortunately, fully successful matching has been limited to half of the array, due to a sensor problem on one capacitor. Operation of the entire array awaits incorporation of additional monitoring.

Figure 9 shows the highest level of power coupled to date from the half array in both (a) Lmode and (b) H-mode (with small type III ELM’s). The rapid changes in power seen on trace (b) reflect the variations in coupling during the ELM’s. The original ILA power specification was estimated by extrapolation of data from the A2 antennae. More recently, the TOPICA computer code [14] has become available for estimating such coupling, and has been used for the ITER and Tore Supra antennae [15,16]. A TOPICA model has now been produced for the ILA (Figure 10), using a curved aperture/slab plasma approximation [14] plus measured data for the plasma scrape-off layer, and comparison with the measured data is underway.

The SHAD system has been tested, but no sub-harmonic signal has yet been observed at the presently chosen measurement positions during JET ILA commissioning, even though such signals have been observed when the system has been temporarily connected to the JET A2 antennas. Work is ongoing to understand this effect and its implications for the wider use of SHAD systems. The SMAD system uses RF signals to derive an error signal that can be compared in real-time against the theoretical RF performance of the ILA [9]. Should differences between the measured and predicted signals persist for longer than 3 successive cycles of 2ms, the RF generators will be tripped. The principle that arc-free RF pulses can run through without false tripping has now been tested on plasma. Figure 11 shows the error signal D obtained by post-processing of the RF signals for JET Pulse No: 73987. The computed signal remains well within the levels at which the SMAD electronics would initiate a trip (shown as dotted lines) despite the clear change from L-mode to H-mode plasma (and the consequent large variations in coupling) during most of the shot (one trip during the pulse plus transients at the start and end of the pulse); thus suggesting that the SMAD system would indeed allow the ILA to remain powered throughout typical JET shots.

ELM tolerance for the full range of JET plasmas requires the ILA to be operated at a real component of the T-point impedance close to 3W. In order to ensure that arcs close to the Tpoint can be detected whilst the SMAD system is not operational, it has been necessary to maintain this impedance at 6W. Despite this limitation, the antenna has demonstrated the capability to operate through small type III ELM’s, with the highest level of ELM tolerance achieved to date shown in Figure 9b.

CONCLUSIONS

Strategic upgrades to three JET ICRF systems have been carried out to increase coupled power in ELMy plasmas using both 3dB and conjugate-T systems. Initial results have tested features of the proposed ITER ICRF system on ITER-relevant JET plasmas, as summarised in Table 1. The JET results to date complement those achieved on Tore Supra in suggesting that close-packed arrays can couple through small ELM's (or equivalent coupling variations on Tore Supra).

The ILA project represents a major step forward in the design and procurement of such ICRF antennae; experience that will be invaluable in the future EU contribution to the ITER antenna design process. Matching of this new antenna has shown that it is feasible to match such antennas at reduced vertical septa depth, thus allowing operation at coupled power densities of relevance to ITER.

Work is underway to: test operation of such systems with larger ELM's; commission all three systems to high power; and to commission the relevant arc detection systems.

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ITER Antenna Issue	JET Objectives	Status
Simultaneous matching of four RDLís	• ILA to match 4 RDL's simultaneously. • Matching through L/H transition.	• Matching successful for 2 RDL's across a range of plasma scenarios (including the L/H transition) and two frequencies. • ILA matching with 4 RDL's ongoing.
>8MW/m^2 coupled	• ILA to couple 7.2MW	• Coupling in L-mode at low ROG confirms close-packed array can achieve target.
ELM Tolerance	• 3dB, ILA and ECT to power through type I ELMís.	• 3dB and ECT systems successful. • ILA successful with atypically small ELM's. Testing with larger ELM's awaits successful arc detection.
Detection of arcs at low impedance positions	• SHAD and SMAD to operate on the ILA. • New arc detection on ECT.	• Sub-harmonic noise not observed on ILA. • SMAD commissioning underway. • ECT: AWACS system being commissioned.
Input to ITER on edge issues (coupling, sheath effects, etc.)	• Experimental data from 3dB, ILA and ECT at ITER-relevant plasma conditions.	• Awaiting commissioning of the antenna for use within the JET programme.

Table 1: Status of testing key antenna features on JET.

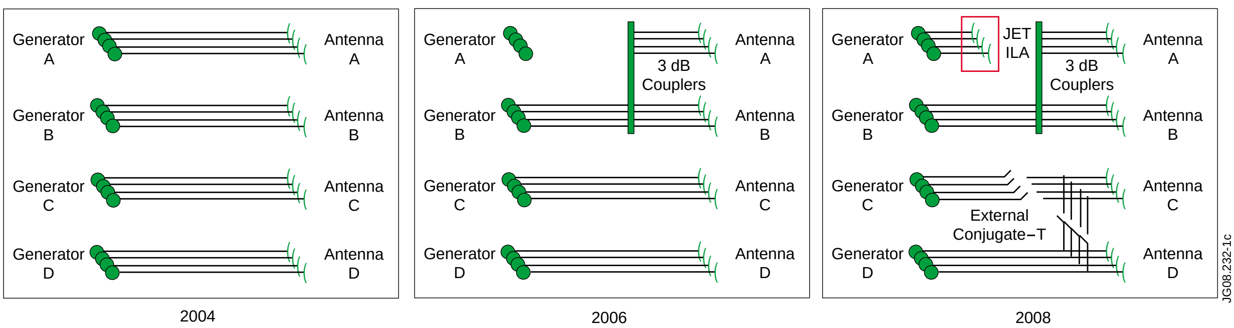

Figure 1: Recent Evolution of the JET ICRF Configuration.

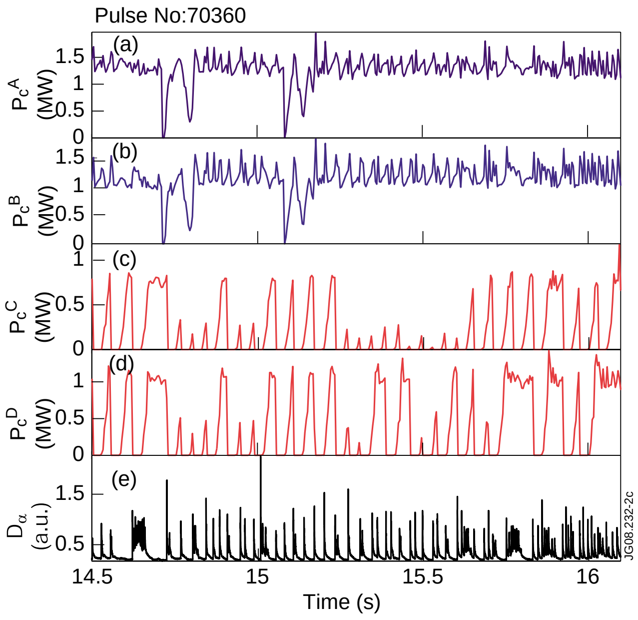

Figure 2: ELM Tolerance using 3dB Couplers. (a), (b):Power coupled from antennae with 3dB (c),(d):Power coupled from antennae without 3dB (e):D_α Signal.

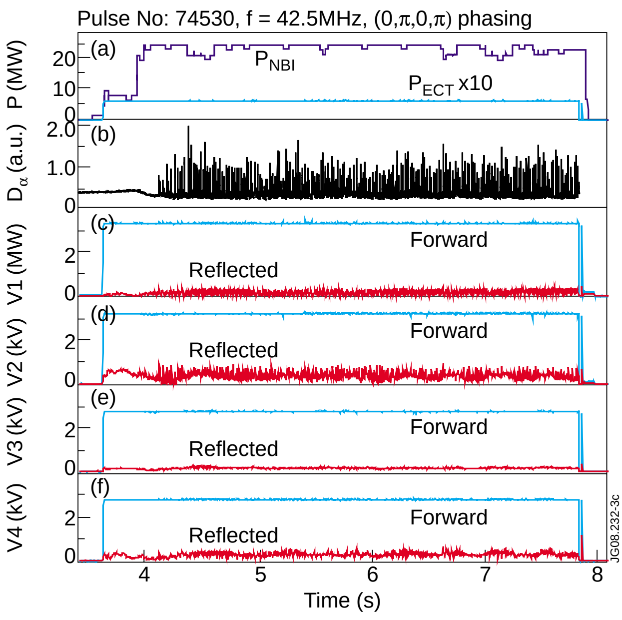

Figure 3: ECT Commissioning on JET (a) Generator & NBI powers; (b) D_α; (c)-(f) Forward & reflected voltages on strap pairs 1-4.

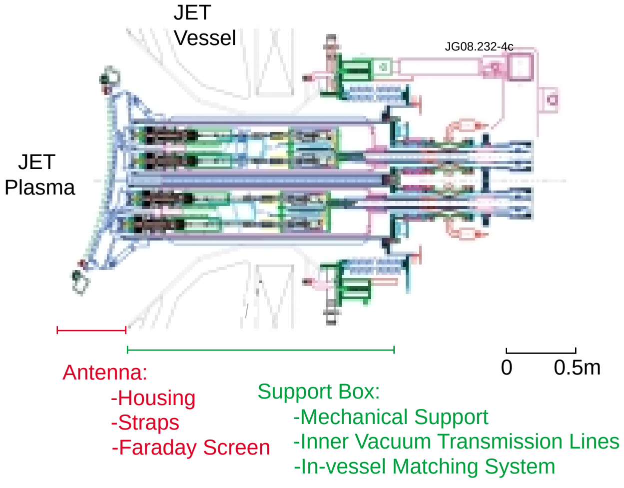

Figure 4: Cross Section of the JET ILA.

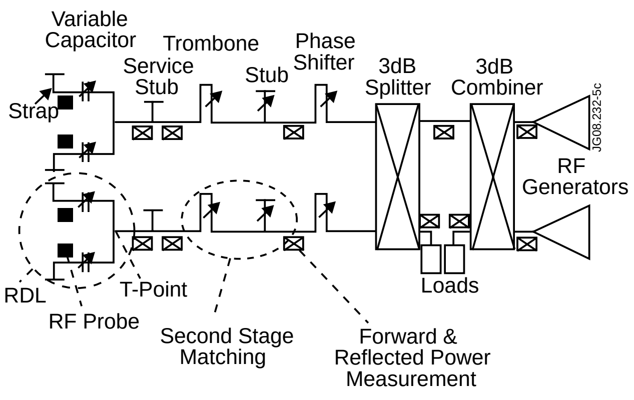

Figure 5: The ILA RF Circuit.

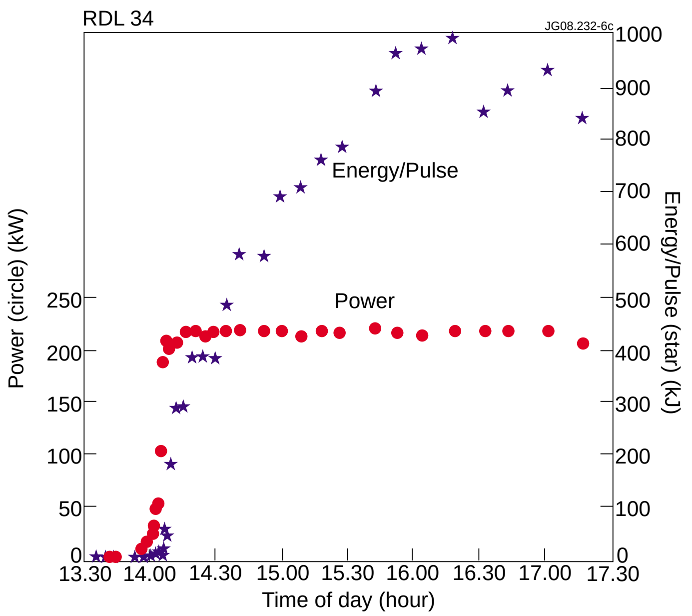

Figure 6: Power and energy/pulse during high power commissioning of RDL34.

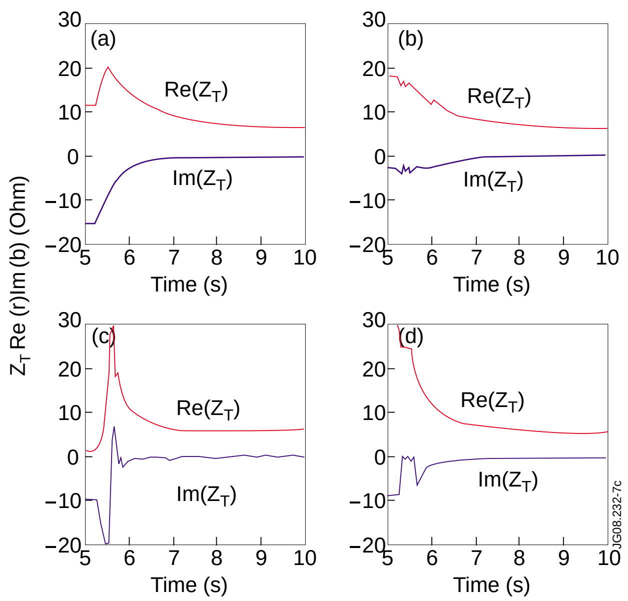

Figure 7: Matching of the full array to target real and imaginary impedances (6-0j Ω) at 42MHz: (a) RDL12, (b) RDL56, (c) RDL 34, (d) RDL 78.

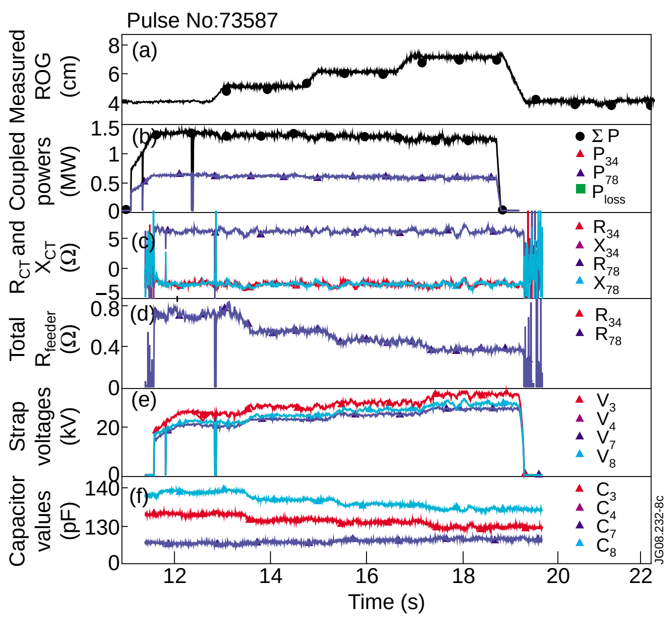

Figure 8: Matching of the half of the antenna in L-mode at 4-7cm varying ROG (JET Pulse No: 73587) (a) ROG, (b) Coupled Power, (c) Antenna Impedance, (d) Coupling Resistance, (e) Strap Voltage, (f) Capacitor Value.

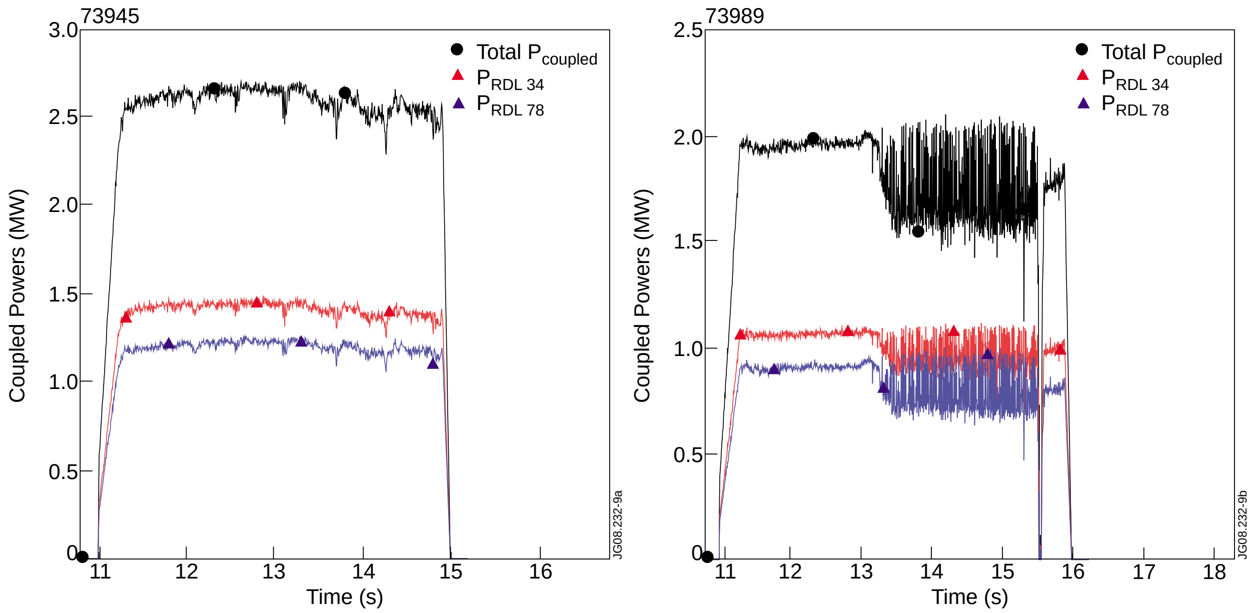

Figure 9: Highest Powers Coupled by Half the ILA Array at 42MHz and 4/5cm ROG (red: RDL34, blue: RDL78, black: total). (a) 2.55MW in L-mode (JET Pulse No: 73945). (b) 1.73MW in H-mode (JET Pulse No: 73989, with L/H transition at 13.3s).

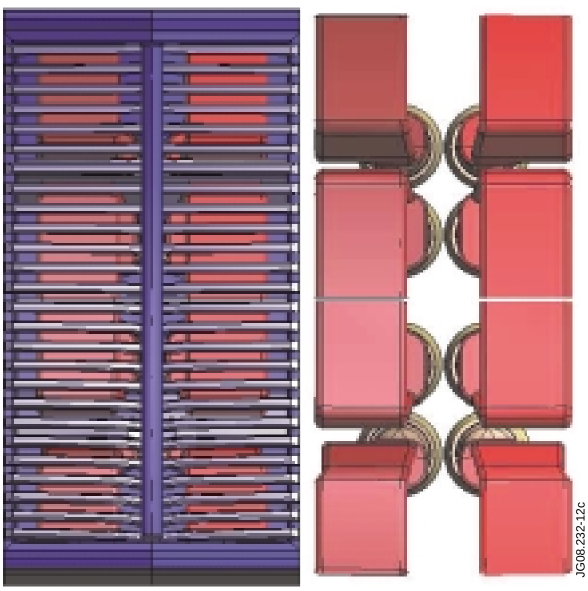

Figure 10: TOPICA Model.

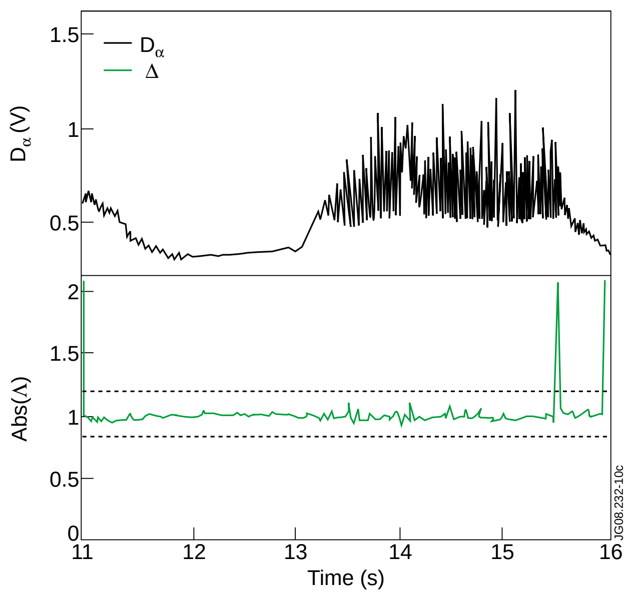

Figure 11: JET Pulse No: 73987- Upper: D_α Signal Lower: SMAD Error Signal Δ (allowed Δ range shown by dotted lines).