

I. Monakhov, M. Graham, T. Blackman, M.-L. Mayoral, M. Nightingale,  
H. Sheikh, A. Whitehurst and JET EFDA contributors

# Operations of the External Conjugate-T Matching System for the A2 ICRH Antennas at JET

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# Operations of the External Conjugate-T Matching System for the A2 ICRH Antennas at JET

*JET-EFDA, Culham Science Centre, OX14 3DB, Abingdon, UK*

<sup>1</sup>*EURATOM-UKAEA Fusion Association, Culham Science Centre, OX14 3DB, Abingdon, OXON, UK*

*\* See annex of F. Romanelli et al, "Overview of JET Results",  
(Proc. 22<sup>nd</sup> IAEA Fusion Energy Conference, Geneva, Switzerland (2008)).*

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## **ABSTRACT.**

The External Conjugate-T (ECT) matching system was successfully commissioned on two A2 ICRH antennas at JET in 2009. The system allows trip-free injection of RF power into ELMy H-mode plasmas in the 32–52 MHz band without antenna phasing restrictions. The ECT demonstrates robust and predictable performance and high load-tolerance during routine operations, injecting up to 4 MW average power into H mode plasma with Type-I ELMs. The total power coupled to ELMy plasma by all the A2 antennas using the ECT and 3dB systems has been increased to 7MW. Antenna arcing during ELMs has been identified as a new challenge to high-power ICRH operations in H-mode plasma. The implemented Advanced Wave Amplitude Comparison System (AWACS) has proven to be an efficient protection tool for the ECT scheme.

## **1. INTRODUCTION**

Following a successful proof-of-principle test [1] the External Conjugate-T (ECT) matching system [2, 3] was installed on two out of four A2 ICRH antennas at JET [4]. The system comprises four identical circuits (Fig.1) each involving a pair of straps belonging to different four-strap antennas C and D. The phase shifters in the CTL and DTL lines are used to set and automatically control the T-junction impedance at a low value  $\text{Re}(Z_T) \cong 3\text{-}4 \text{ Ohm}$ ,  $\text{Im}(Z_T) \leq 0 \text{ Ohm}$ , which ensures low sensitivity of the amplifier output VSWR to strong antenna loading perturbations during ELMs.

## **2. COMMISSIONIN STATUS**

The ECT system has been commissioned at the fixed frequencies of 32.5MHz, 42.5MHz, 46.0MHz and 51.0MHz covering the majority of JET operational scenarios. Simultaneous matching of all four ECT circuits has been successfully achieved under a variety of antenna loading conditions including vacuum, L mode plasmas with ‘sawtooth’ activity and ELMy H-mode plasmas with mid-plane limiter-separatrix distances in the range of 4–14cm. Most of the experiments were performed at standard  $(0, \pi, 0, \pi)$  phasing of the antenna straps; transition to alternative phasings, such as  $\pm(0, \pi/2, \pi, 3/2\pi)$  and  $(0, \pi, \pi, 0)$  has been found to be straightforward.

The algorithms [3] for automatic adjustment of the lengths of the CTL and DTL phase shifters have been successfully tested. The real-time control facilitates initial matching in new experimental conditions and allows tracking of the antenna loading changes during slow plasma evolution.

Overall, the ECT has demonstrated robust and predictable performance; the project milestones have been met, and the system is being used routinely during ICRH operations.

## **3. THE ECT SYSTEM BEHAVIOUR DURING ELMS**

Experiments in ELMy plasma conditions have confirmed the expected high load-tolerance of the ECT circuit. The dependence of the VSWR in the RF amplifier Output Transmission Line (OTL) on the antenna strap coupling resistance (Fig.2) measured during ELMs has shown all the textbook features of the conjugate-T matching, as well as good consistency with simulations based on realistic input parameters. The fast VSWR perturbations during all types of ELMs have typically remained well below the VSWR=3 protection trip threshold. This allowed trip-free amplifier operations and

continuous power injection even during big ( $\Delta W_{\text{DIA}} \leq 0.7\text{MJ}$ ) Type-I ELMs accompanied by strong changes of antenna resistive and inductive loading (Fig.3).

The observed momentary increase in the power levels coupled to plasma during ELMs (Fig.3e) is explained by reduction of power losses in the antenna and transmission lines during high loading conditions. This increase can make a noticeable contribution to the average power levels coupled to H-mode plasma with frequent ELMs.

#### **4. HIGH POWER PERFORMANCE DURING ELMY PLASMA**

Depending on the JET discharge scenario, the trip-free time-average power levels coupled to ELMy H mode plasma by the ECT system during long pulses have reached 4MW. Availability of the ECT system, together with the 3dB splitters [5], has made it possible to increase the total RF power coupled to ELMy plasma by all four A2 antennas to 7MW (Fig.4). Further progress requires more effort for antenna conditioning at voltages exceeding 30kV.

#### **5. OBSERVATION AND DETECTION OF ARCS DURING ELMs**

Successful implementation of ELM-tolerant matching revealed a new challenge to high-power ICRH operations in H-mode plasmas. Together with the well-documented high voltage breakdown between ELMs, occurrences of antenna arcs during ELMs (Fig.3) are suspected despite substantial reduction of the voltages in the presence of high antenna loading (Fig.5). Consistent with simulations [3], the traditional arc detection method based on observation of the VSWR in the matched transmission line (OTL) was found inadequate to trigger the protection trip under these conditions (Fig.6). A new Advanced Wave Amplitude Comparison System (AWACS) [3] has been implemented to cope with the problem. The AWACS monitors the ratios of the OTL reflected and CTL & DTL forward voltages  $V_{\text{REF}}^{\text{OTL}}/V_{\text{FOR}}^{\text{OTL}}$  &  $V_{\text{REF}}^{\text{OTL}}/V_{\text{FOR}}^{\text{OTL}}$  (Fig.1) which demonstrate high sensitivity to arcs (Fig.6). The routine use of the AWACS at JET has so far proven highly effective for arc protection of the ECT system.

#### **CONCLUSIONS**

Reliable performance and high tolerance to ELMs has been demonstrated during commissioning of the ECT matching system on two A2 ICRH antennas at JET. Trip free injection of up to 4MW power into plasma with Type-I ELMs has been achieved. Together with the 3dB system, the ECT has brought the total power coupled to ELMy plasma by all the A2 antennas to 7 MW, considerably enhancing JET research capabilities. The implemented AWACS arc detection technique has proven capable of tackling the emerging problem of antenna arcing during ELMs.

#### **ACKNOWLEDGMENTS**

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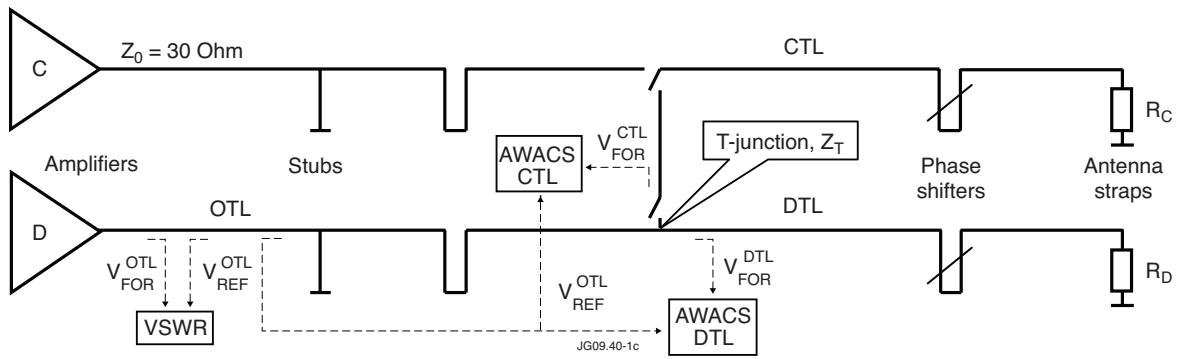


Figure 1. Schematic representation of the ECT system and protection circuits commissioning status

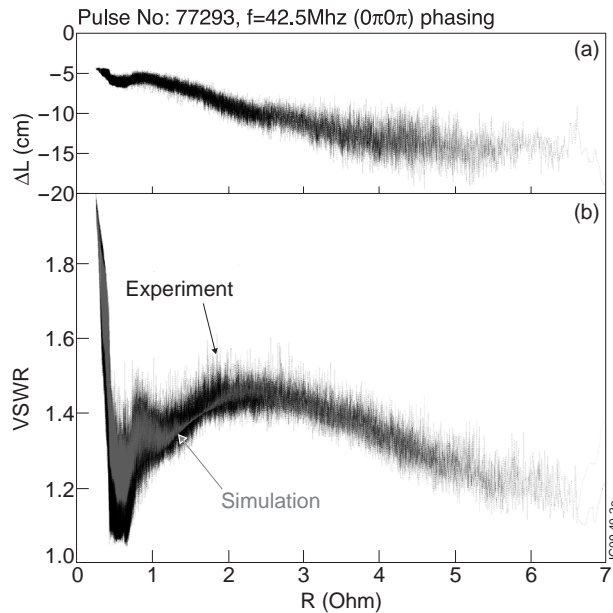


Figure 2: The ECT matching tolerance to antenna loading perturbations during ELMs: (a) the measured dependence of the antenna strap equivalent length deviation from the vacuum value on the strap coupling resistance, (b) the measured (black) and simulated (grey) dependencies of the OTL VSWR on the strap coupling resistance; data for one pair of conjugated straps C4-D4 with  $5\mu\text{s}$  sampling over 200 consecutive ELMs. The VSWR simulations use the data shown on plot (a) as an input and assume the ECT settings relevant to the experimental conditions.

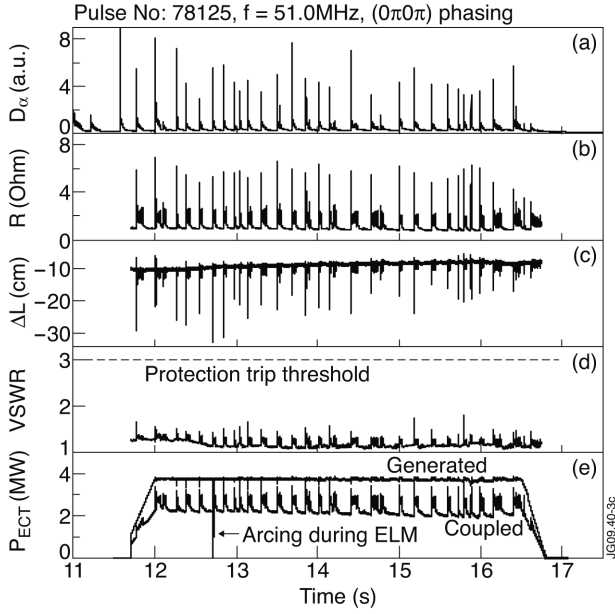


Figure 3: The ECT behavior during big ELMs: (a) mid-plane  $D_{\alpha}$  line emission intensity, (b) antenna strap coupling resistance, (c) antenna strap equivalent length deviation from the vacuum value, (d) OTL VSWR, (e) RF power generated and coupled to plasma by the ECT system. Plots (b), (c) and (d) correspond to the values averaged over the four constituent ECT circuits; 5ms RF data sampling.

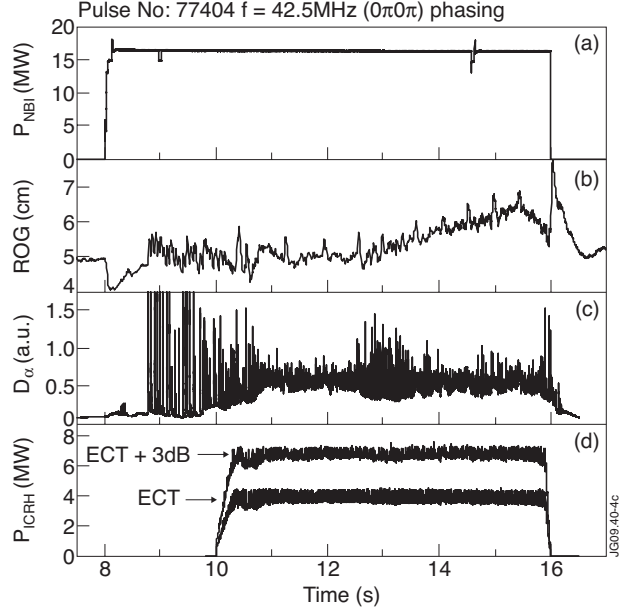


Figure 4: An example of trip-free high power performance of the ECT and 3dB systems during ELMy plasma: (a) neutral beam power, (b) mid plane distance between the separatrix and A2 antenna limiters, (c) mid plane  $D_{\alpha}$  line emission intensity, (d) maximum antenna voltages in the ECT and 3dB systems (e) RF power coupled to plasma by the ECT system and the total RF power coupled by all the A2 antennas.

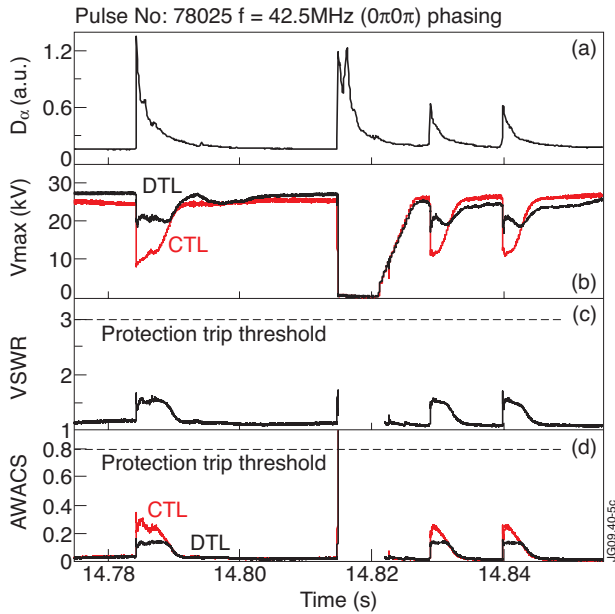


Figure 5: The VSWR and AWACS signals response to ELMs and suspected ELM-induced arc: (a) mid plane  $D_{\alpha}$  line emission intensity, (b) maximum voltages in the conjugated lines, (c) OTL VSWR, (d) CTL and DTL AWACS signals. The plots correspond to the C3-D3 pair of straps; 5 $\mu$ s RF data sampling.

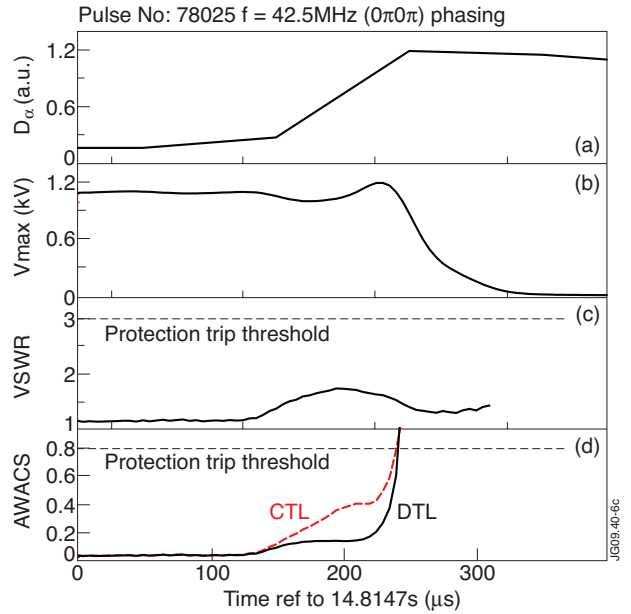


Figure 6: The short time-scale representation of the AWACS triggered arc protection trip shown in Fig.5: (a) mid plane  $D_{\alpha}$  line emission intensity; note 100 $\mu$ s sampling for this trace, (b) RF power on the output of the amplifier D3, (c) OTL VSWR, (d) CTL and DTL AWACS signals.