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ABSTRACT

The External Conjugate-T (ECT) matching system is planned for installation on two A2 ICRH antenna arrays at JET in 2007. This will enhance the operational capabilities of the RF plant during ELMy plasma scenarios and create new opportunities for ITER-relevant matching studies. The main features of the project are discussed in the paper focusing on the specific challenges of the ECT automatic matching and arc detection in optimized ELM-tolerant configurations. A 'co/counter-clockwise' automatic control mode selection and an Advanced Wave Amplitude Comparison System (AWACS) complementing the existing VSWR monitoring are proposed as simple and viable solutions to the identified problems.

INTRODUCTION

The External Conjugate-T (ECT) [1] is a method of load-tolerant matching of ICRH antennae in tokamaks which allows continuous RF power injection into H-mode plasmas during occurrence of ELMs. Following a successful proof-of-principle test [2], the ECT is currently being installed on two A2 ICRH antenna arrays at JET. The ECT will complement the alternative approaches of tackling the ELMs available for the A2 antennae - diverting the RF power into a dummy load using the hybrid couplers [3] and momentary power tripping [1]. This creates a unique opportunity to compare the methods in the same experimental environment and to assess the implications of RF power injection into ELMs which remains an important issue for ITER.

THE ECT PROJECT FEATURES

The ECT system comprises four identical circuits (Fig.1) each involving a pair of similar straps belonging to different A2 ICRH antennae (four-strap arrays C and D). The conjugation of remote straps allows arbitrary array phasing and minimises the adverse influence of mutual coupling. The phase shifters installed in the lines CTL and DTL between the straps and the T-junction are automatically controlled to match slow loading changes, while the tolerance to fast coupling perturbations is achieved by setting the reference impedance Z_T to a low real value $\mathrm{Re}(Z_T) \cong 3\text{-}5\ \Omega \ll Z_0 = 30\ \Omega$ (Z_0 is the line characteristic impedance) [1]. Allowing for a small reactance $\mathrm{Im}(Z_T) \neq 0$ at the T-junction could help to cope with the ELM-induced strap reactance changes; this, however, has certain implications for reliability of the ECT automatic matching and arc detection (see below). The main transmission line (MTL) stub tuner is not under a real-time control - it is needed only to complete the Z_T-to-Z_0 transformation.

For maximum flexibility the conventional JET matching method by stub tuners [4] is retained in the project with a possibility of remote switchover between plasma pulses. The system is expected to couple up to 5 MW free of trips into ELMy plasmas at all common ICRH frequencies over the 31-57 MHz band except for the 37±2 MHz (restrictions due to insufficient variable length of the MTL phase shifter).

ENHANCEMENT OF AUTOMATIC MATCHING CONTROL

The ECT automatic matching algorithm relies on the same error signals that are used in the conventional JET matching system [4]: Re(E) and Im(E), where $E = V^{OTL}_{REF} / V^{OTL}_{REF}$ (see Fig.1). Each of the signals independently controls the length of the CTL and DTL phase shifters. For reduction of the response time the speeds of the length variation of both elements are normally set to equal maximum values. In this situation the matching algorithm is defined solely by the error signal signs which determine the direction of the CTL and DTL length change required for reaching the OTL VSWR=1 target. (Note, that generally there exist two matching targets corresponding to the conditions of $L_{CTL}>n\cdot\lambda/2>L_{DTL}$ and $L_{DTL}>n\cdot\lambda/2>L_{CTL}$, where the L_{CTL} and L_{DTL} are the total CTL and DTL lengths from the load to the T-junction and $n\cdot\lambda/2$ is a whole number of half-wavelengths in each line [1]).

Depending on the adopted sign logic and on the Re(E) and Im(E) signal allocation to the CTL or DTL phase shifter, two control modes are feasible: one drives the matching trajectory to the target in a 'clockwise' and another in a 'counter-clockwise' manner in the space of the CTL and DTL lengths (Fig.2a). Because the error signal patterns in a simple case of purely resistive T-junction reference impedance $Im(Z_T)=0$ and equally loaded conjugated straps $R_C=R_D$ are totally symmetric (Fig.2b), the modes were originally considered equally reliable, and only one of them was available during the proof-of-principle test [2]. Subsequent in-depth analysis has shown, however, that setting the T-junction to a non-zero reactance $Im(Z_T)\neq0$ or asymmetric strap loading $R_C\neq R_D$ makes the behavior of the two control modes quite different - depending on the selected matching target, the $Im(Z_T)$ sign and the $R_C>R_D$ or $R_C<R_D$ condition, one of the modes appears to be prone to failures (Fig.2c).

In order to resolve the problem, the ECT electronics are now designed to accommodate both the 'co-' and 'counter-clockwise' control modes with a possibility of remote selection. The decision on which of the modes to use will be taken by the RF plant operator as a part of the ECT performance optimization procedure prior to operations in specific experimental conditions.

ADVANCED ARC DETECTION SYSTEM

The protection of the ICRH antennae and transmission lines against high voltage arcing is normally provided at JET by the high-VSWR trip system which compares the amplitudes of reflected and forward voltage waves in the matched amplifier output transmission line (OTL). In the conventional stub tuner matching scheme the technique proved to be quite reliable for all but relatively unlikely voltage-node arcs [5]. Simulations performed for the ECT circuit have shown that the VSWR monitoring could fail to detect arcs in one of the conjugated lines under certain operational conditions including non-zero T-junction reactance $Im(Z_T)\neq0$ settings, the CTL or DTL length deviation from the matching target and during ELMs (Fig.3).

A new simple complementary method was proposed utilising the existing arc detection hardware and electronics and improving the ECT arc protection in the above mentioned circumstances (Fig.3). The Advanced Wave Amplitude Comparison System (AWACS) operates similarly to the

VSWR technique with the only difference that the compared reflected and forward voltage wave amplitudes are measured in different parts of the circuit (Fig.1), specifically in the OTL and CTL (DTL) respectively. The $V^{REF}_{OTL}/V^{FOR}_{CTL}$ and $V^{REF}_{OTL}/V^{FOR}_{DTL}$ ratios are much more sensitive to arcing in the CTL or DTL than the $V^{REF}_{OTL}/V^{FOR}_{CTL}$ ratio because an arc not only mismatches the OTL increasing the V^{REF}_{OTL} but also asymmetrically detunes the T-junction and reduces the forward power going into the arcing line.

CONCLUSIONS

The planned installation of the External Conjugate-T system on the existing A2 ICRH antennae at JET will enhance capabilities of the RF plant during operations in ELMy plasmas and open new opportunities for experimental assessment of different technologies of RF power injection into a quickly variable load.

The in-depth analysis of the expected ECT performance in the expanded range of operational scenarios and optimised ELM-tolerant settings revealed the necessity of improvement of the originally adopted strategy of automatic matching and arc detection. The proposed method of selectable ‘co-‘ and ‘counter-clockwise’ control modes and the Advanced Wave Amplitude Comparison System (AWACS) appear as simple, inexpensive and viable solutions to the identified problems.

ACKNOWLEDGMENTS

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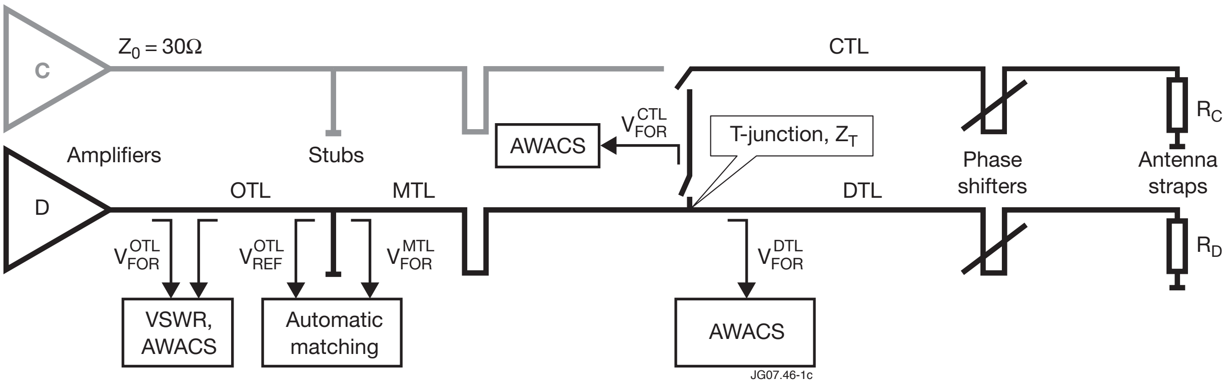
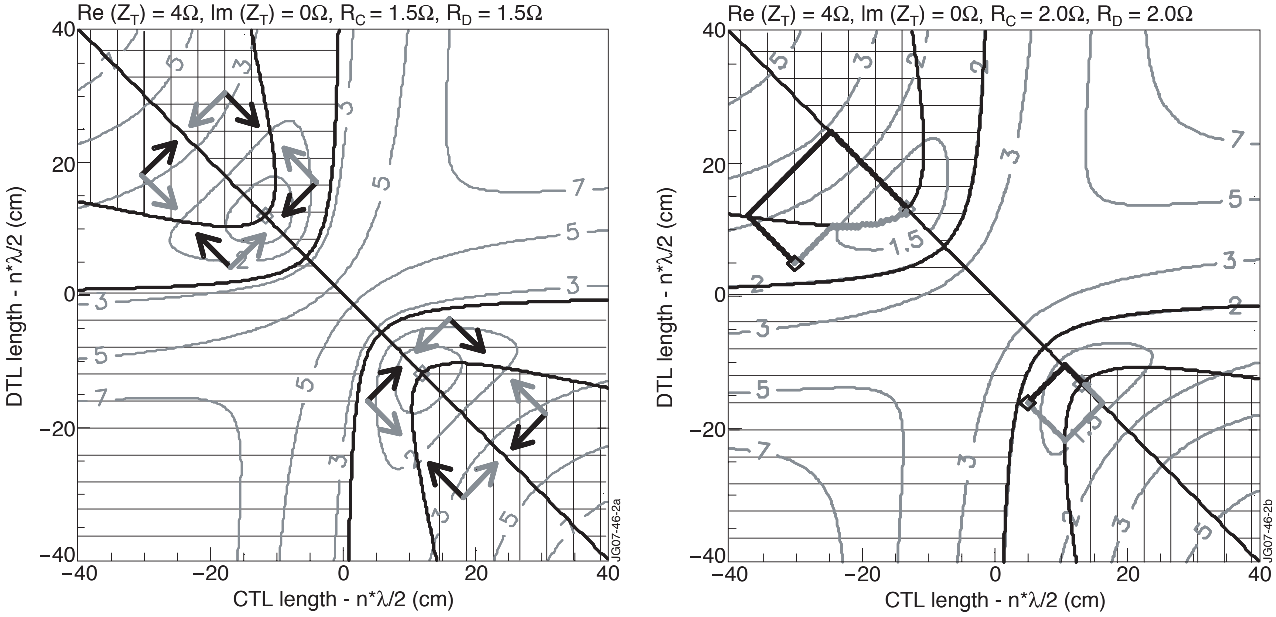


FIGURE 1. Schematic diagram of one of the four identical ECT circuits and associated control signals.



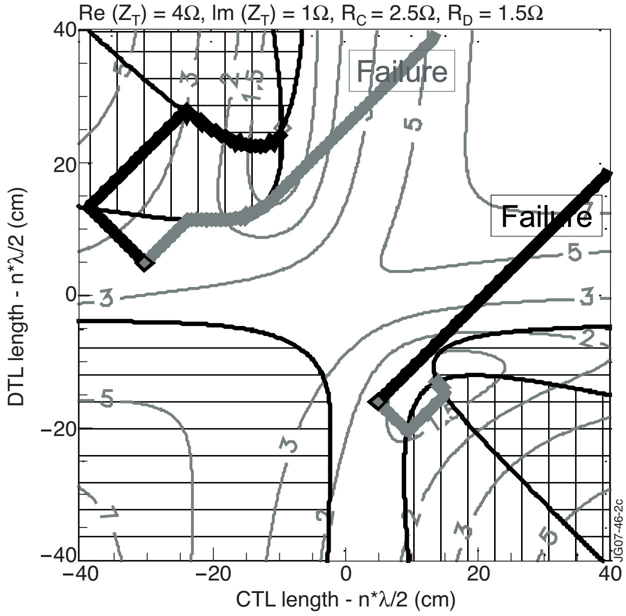
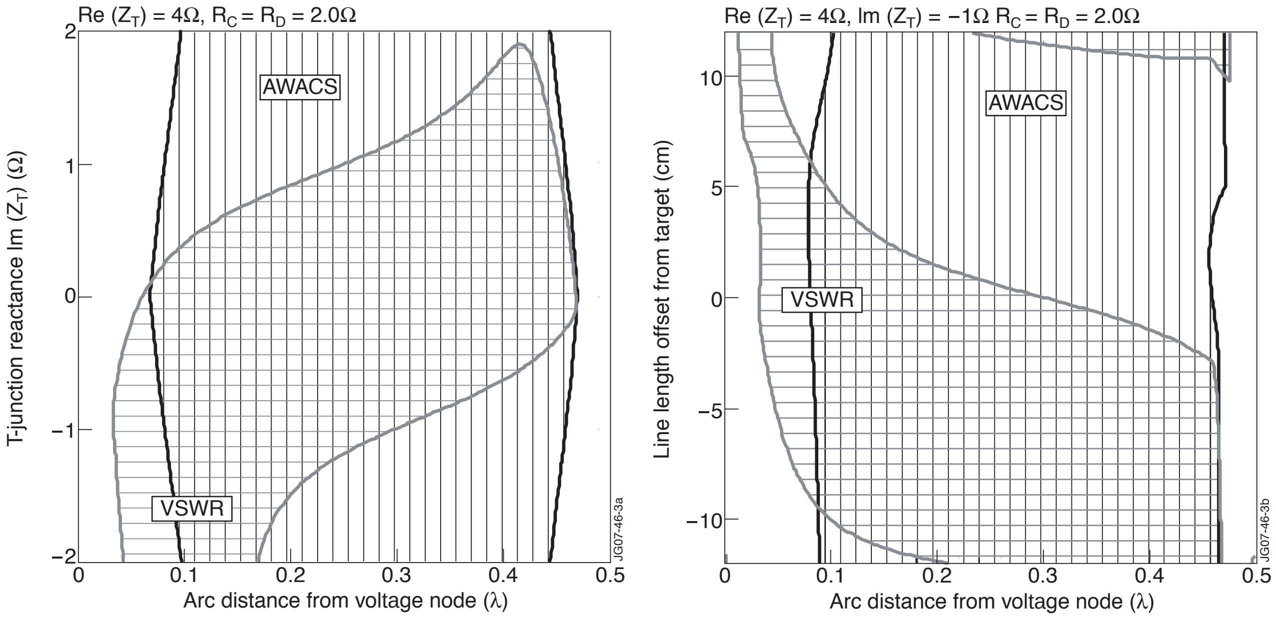


FIGURE 2. Simulations of the ECT automatic matching algorithm at f=42 MHz. The areas filled with the horizontal and vertical lines denote the conditions of Re(E)<0 and Im(E)<0 respectively and the grey contours show the OTL VSWR behavior. The axes represent the CTL and DTL total lengths modulo some multiple of the half-wavelength. The black and grey arrows and traces correspond to the 'co- 'and 'counter-clockwise' control modes respectively: (a) Adopted matching logic of the line length control around the two existing VSWR=1 targets for various combinations of the error signal signs, (b) and (c) - examples of matching trajectories for the cases of Im(ZT)=0, RC=RD and Im(ZT)=/0, RC=/RD.



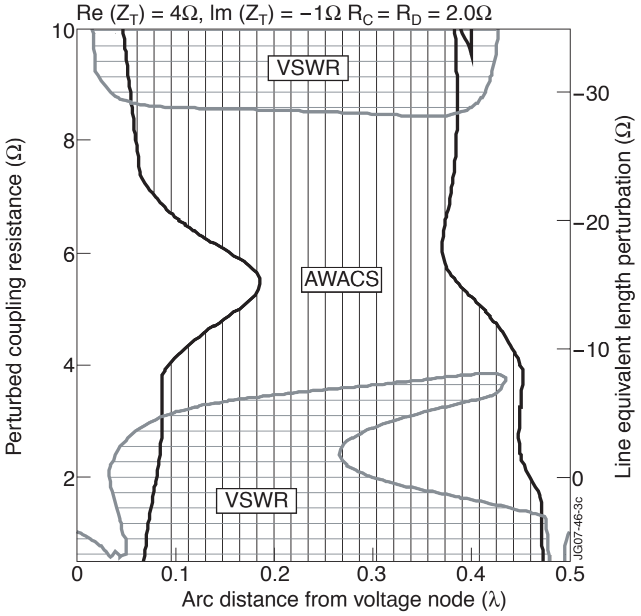


FIGURE 3. The ECT arc detection capabilities at f=52 MHz. The areas filled with the horizontal or vertical lines denote the conditions of successful arc detection by the VSWR or AWACS methods respectively. The axes represent the arc distance from a voltage node in the CTL or DTL expressed in terms of line wavelength and (a) T-junction reference reactance, (b) CTL or DTL length offset from the matching value and (c) Symmetric complex perturbation of CTL and DTL loading (i.e. idealized ELM).