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ABSTRACT

A prototype of ICRF antenna matching system tolerant to fast plasma loading perturbations has been successfully tested at JET. The technique is based on the use of an external (outside the tokamak vacuum vessel) conjugate-T circuit tuned to low resistive impedance by coaxial line-stretchers (trombones). Further impedance transformation, required to complete the entire circuit matching is achieved by a conventional variable stub and trombone tuner. The experimental set-up involved one pair of adjacent straps of the JET A2 antenna array powered by a single RF amplifier. The tests fully confirmed the feasibility of the matching scheme both for vacuum and plasma loading. Clear evidence of high load tolerance during plasma sawtooth oscillations and Edge Localised Modes (ELMs) was observed in agreement with the circuit simulations. Reliable trip-free performance was demonstrated in the 32-51MHz frequency band at 1MW power levels. The proposed approach appears as a viable alternative to the in-vessel conjugate-T matching schemes and offers such additional advantages as reliance only on well-established coaxial line technology, manageable tuning accuracy, separation of launching and matching sub-systems and capability to conjugate remote antenna straps.

INTRODUCTION

Antenna matching during strong and fast loading perturbations introduced by ELMs is one of the major challenges of high power ICRF operations in H-mode plasmas both on present-day tokamaks and on ITER. The principle of conjugate-T matching offers a promising general approach to the problem and the methods for its implementation on tokamaks have been the focus of attention lately [1]. A new ITER-like' antenna based on in-vessel conjugate-T matching by vacuum capacitors is being developed on JET [2]. A complementary technique to improve the ELM-tolerance of the existing JET A2 antennas [3] by using the external (outside the vacuum vessel) conjugate-T circuit tuned by coaxial phase-shifters (trombones) was also proposed [4]. The latter approach does not imply matching system integration into a dedicated ICRF launcher, which opens an opportunity to conjugate the straps belonging to different antenna arrays and, thus, to ensure an arbitrary antenna phasing. The method relies entirely on well-established coaxial line technology with manageable accuracy of control of the matching elements. A successful experimental assessment of the trombone-tuned external conjugate-T matching scheme was recently performed at JET and the main results of the tests are presented below.

1. EXPERIMENTAL SET-UP

The tests were conducted on one half of the JET ICRF module 'C' and involved one pair of adjacent radiating straps powered by a single RF amplifier (Fig.1). The trombones installed between the straps and the T-junction were used to tune it to a low and purely real impedance, R_T=3-6 Ohm, which is necessary to ensure high load-tolerance of the circuit [4]. Further impedance transformation required to accomplish the amplifier Output Transmission Line (OTL) matching to 30 Ohm was provided by a variable trombone and stub tuner. The lengths of the impedance transformer elements, which depend only on the chosen values of RT and the frequency, were normally fixed. The lengths of the conjugate-T trombones were adjusted between the pulses or under the automatic real-time control to accommodate the variable antenna loading.

2. MATCHING TO THE QUASI-STATIONARY LOAD

The available accuracy of trombone length control (~3mm) proved to be quite sufficient to ensure a perfect matching even in the most challenging case of vacuum loading when low circuit losses reduce the matching target to a minimum (Fig.2). RF operations with OTL VSWR≤1.1 corresponding to either of the two existing conjugate-T matching solutions A and *B* were attained at five representative frequencies in the 32-53MHz band both under vacuum and L-mode plasma loading. Manual pulse-to-pulse adjustments originally used to achieve the results were later supplemented by an automatic control. It was found that the error signals *Re(V- /V+)* and *Im(V- /V+)* (see Fig.1) used by the existing JET matching system [5] could be easily adapted for frequency-independent real-time control of the conjugate-T matching elements. A typical behaviour of the conjugate-T circuit under quasi-stationary loading is illustrated on Fig.3

3. TOLERANCE TO FAST LOADING PERTURBATIONS

The circuit resilience to fast antenna-plasma coupling perturbations was assessed during discharges with strong sawtooth activity, L-H mode transitions and ELMy H-mode regimes. In general, the tested scheme has shown noticeably higher loadtolerance as compared with the conventional matching system, which resulted in better waveform control and increased average levels of the power generated by the RF amplifier involved (Fig.4). Reliable RF performance was demonstrated during ELMy plasmas with fast coupling resistance excursions reaching 8-9 Ohm (Fig.5). The measured amplifier output VSWR increase during ELMs remained below the VSWR=3 protection trip threshold and was in good agreement with the circuit simulations (Fig.6). Loading asymmetry and strong strap electrical length perturbations ($\delta L_c \leq 40$cm) in hightriangularity plasmas [6] were identified as the main negative factors affecting the VSWR response to ELMs. Judicious choice between the two matching solutions and fine-tuning of the T-junction impedance RT were found useful for ELM-tolerance improvement under these circumstances.

Predictably, the load-sensitive current phase difference in the conjugated straps changed from ~±150° in vacuum to ~±135° in L-mode plasma and down to ~±90° during ELMs, where the sign was defined by the used matching solution A or *B*.

CONCLUSIONS

The tests fully confirmed the feasibility of the trombone-tuned external conjugate-T matching scheme both for vacuum and plasma loading. Clear evidence of high ELM-tolerance was observed in agreement with the circuit simulations. Reliable trip-free RF amplifier performance was demonstrated during ELMy plasmas in the 32-51 MHz frequency band at 1MW power levels. Conjugation of identical straps belonging to different JET antennas [4] will remove the strap phasing limitations inherent in the test configuration and balance the strap loading, which could further improve the system performance.

The tests represent the first-ever experimental study of conjugate-T circuit response to ELMs in tokamarks and in this respect the obtained results could provide a valuable input into design of ICRF system on ITER.

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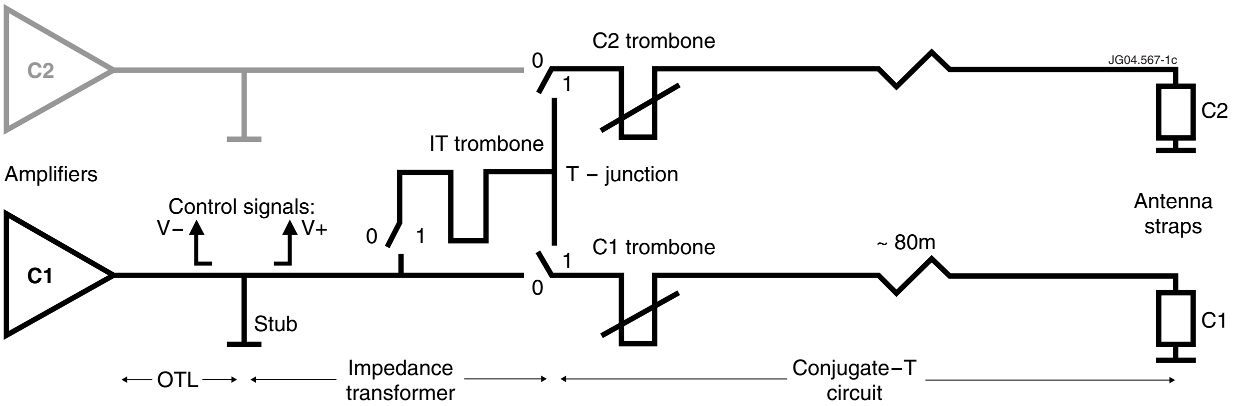

Figure 1. Schematic diagram of the part of JET RF module 'C' involved in the tests. Positions 0 and 1 *of the switches correspond respectively to the conventional and to the load-tolerant matching configurations and could be changed between the tokomak pulses. The second half of the module ('C34') remained in the conventional configuration [5] and was powered only during L-mode plasma cross-talk studies.*

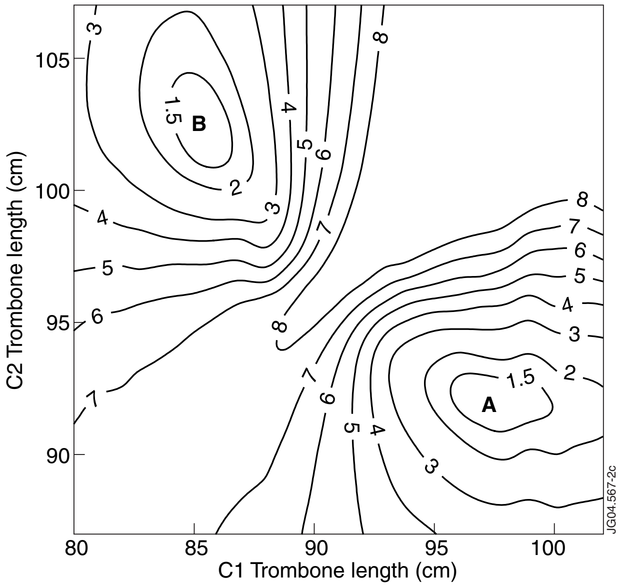

Figure 2. Dependance of Voltage Standing Wave Ratio (VSWR) in the OTL on the lengths of the conjugate-T trombones under the vacuum loading; network analyser measurements at f=42.1MHz, R_T=3 Ohm. The VSWR=1.5 contours circling the two existing matching points A and B give an indication of the minimum matching targets dimensions.

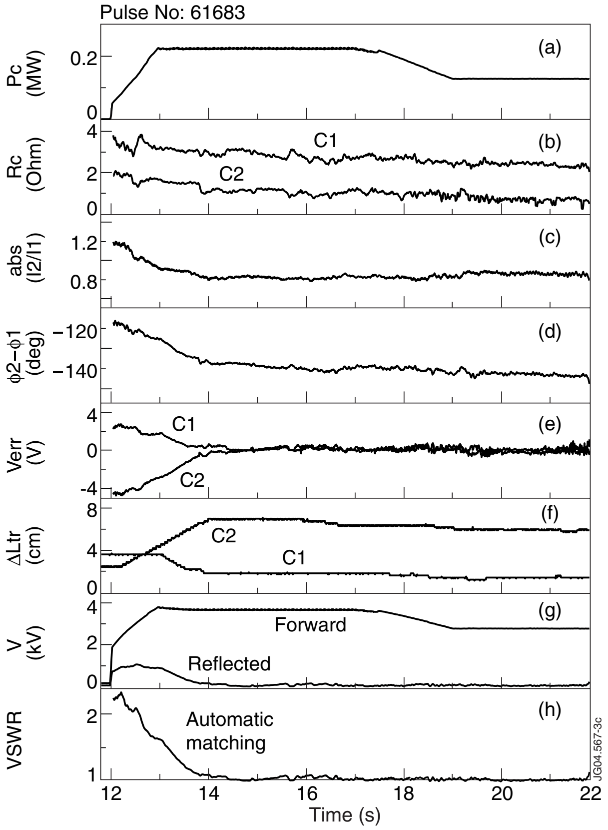

Figure 3. External conjugate-T automatic matching under L-mode plasma loading; f=42.1MHz, R_T=4 Ohm. (a) - generated power, (b) - coupling resistance, (c) - ratio of strap C2 and C1 current amplitudes, 9D0 - strap C2 and C1 current phase difference, (e) - trombone length control error signal voltage, (f) - trombone length deviatioon from the vacuum matching setting, (g) - OTL forward and reflected voltage wave amplitude, (h) - OTL VSWR.

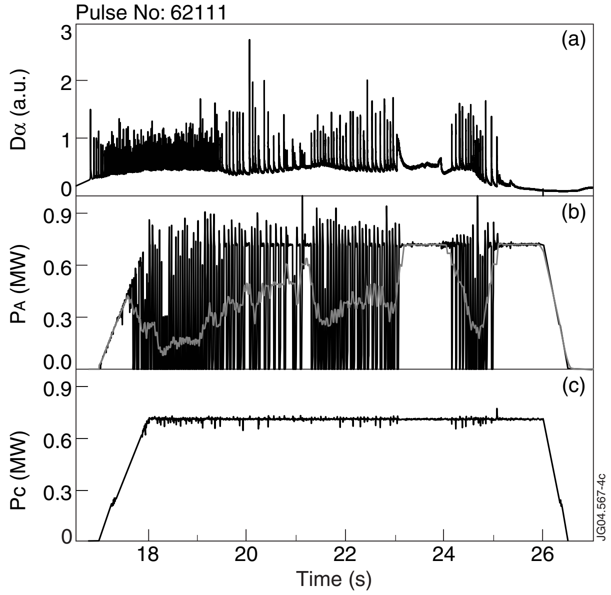

Figure 4. Comparative performance of JET RF modules 'A' (conventional matching) and 'C' (external conjugate-T matching, R_T=3Ohm) during ELMy plasma, f=42.1MHz. (a) - intensity of Dα-line emission from the plasma outer edge; peaks indicate the occurrence of ELMs, (b) - instantaneous and 0.2s windowaveraged power, generated by four amplifiers of module 'A',

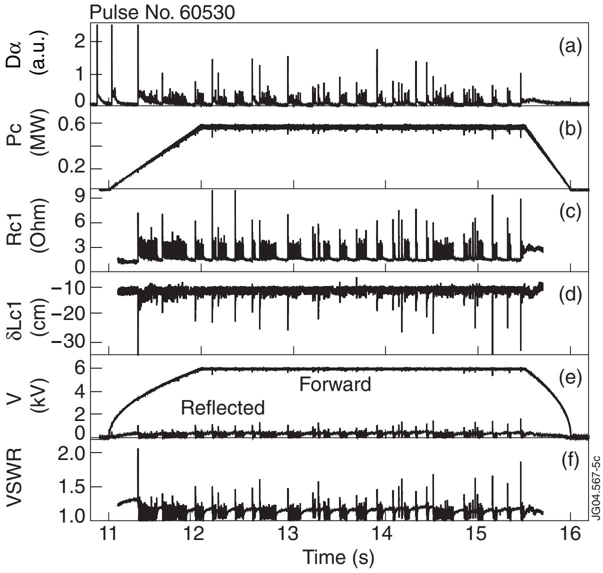

Figure 5. Load-tolerance of the external conjugate-T system during ELMy H-mode plasma; f=42.1MHz, R_T=3 Ohm, no real-time control. (a) - Dα-line emission intensity, (b) - generated power,(c) strap C1 coupling resistance, (d) - strap C1 electrical length pertubation with respect to the vacuum value, (e) - OTL forward and reflected voltage wave amplitude, (f) - OTL VSWR. The presented data were collected at 10kHz sampling rate.

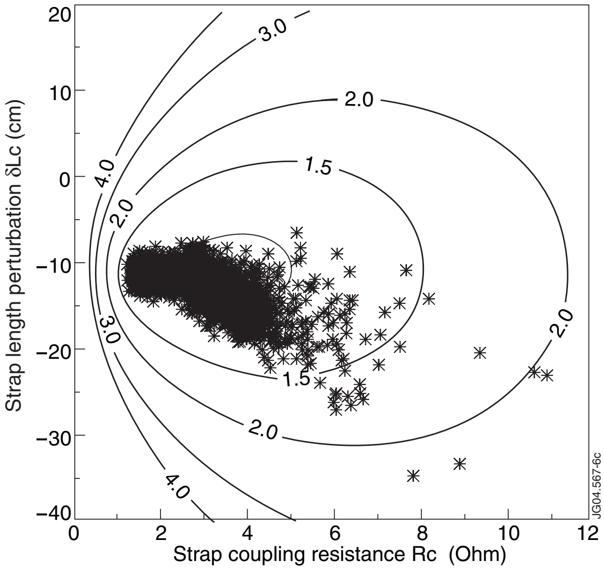

Figure 6. Simulations of the system tolerance to resistive and reactivate loading perturbatios. Contours of OTL VSWR are calculated for the case of f=42.1MHz, R_T=3Ohm and identical loading of both straps. The set of dots represents a measured 'footprint' of strap C1 ELMy plasma loading during pulse no: 50530. (See Fig.5(f) for cross-reference).