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ABSTRACT.

The transmission and matching system of the JET ITER-Like ICRF antenna includes specific design features, contributing to tolerance of the generators to large (dominantly) resistive increases in loading, and to be tested on JET in ITER-relevant ELMy H mode conditions for the first time. Beside the “conjugate-T” circuit, internally matching the launcher to a very low reference impedance, an original adjustable wideband transformer has been designed for compatibility with various ancillary functions. Optional 3dB splitters provide further generator isolation. The paper discusses design choices leading to the final layout and briefly presents the simulated performance of the system.

1. TRANSMISSION AND MATCHING SYSTEM

Beside the characteristics of the antenna array [1], the transmission and matching system of the JET ITER-Like ICRF antenna includes a number of specific design features, (Fig.1):

- (i) The conjugate-T circuit [2] provides internal matching of the launcher over its operating frequency range (30 to 55MHz) by feeding pairs of radiating straps in parallel through adjustable capacitors.
- (ii) A very low reference characteristic impedance Z_0 is used for matching each of the four antenna inputs. These two ingredients make the system tolerant to large increases of the resistive loading of each pair of straps from a matched reference configuration (Fig.2). In the JET implementation a range of values of Z_0 from 3Ω to $\sim 9\Omega$ can be selected, allowing comprehensive investigation of the new scheme. In contrast with the ELM-tolerant scheme based on 3dB hybrids diverting reflected power to dummy loads [3], the internal conjugate-T matching circuit intrinsically keeps reflection low, once suitably configured. Conversely to the wideband matching system previously studied at JET [4], it does not require any adjustment on the ELM timescale.
- (iii) The internal matching stage is followed by an original adjustable impedance transformer between Z_0 and the 30Ω of the JET ICRF transmission lines, described in the following section.
- (iv) Two hybrid 3dB splitters (not shown) share RF power between the four antenna ports. Poloidal and toroidal splitting schemes are under consideration; we focus on the former, which allows full toroidal phasing capability. Line stretchers between splitters and each transformer allow two types of operation: either at maximum generator isolation from residual reflected power, which requires a 90° poloidal phasing between pairs of radiating straps and reduces antenna coupling; or at maximum array coupling (achieved by imposing 180° between input currents due to relative orientation of radiating loops), but reduced generator isolation.

2. DESIGN OF THE IMPEDANCE TRANSFORMER

The transformer specifications are lowest possible return loss between 30 and 55MHz and large transformation ratio (up to 10, to obtain a highly load-tolerant internal matching circuit). Its layout

is severely constrained: part of it is in-vessel; capacitor hydraulic actuating and cooling circuits must penetrate the vacuum boundary along a RF-free path, i.e. inside coaxial line internal conductors. The transformer must also accommodate the RF vacuum window, for which a validated 30 double conical feedthrough (DCF) design was available [5]. These boundary conditions made a standard maximally flat or equal ripple transformer impractical (such a design would also have required a very low first stage impedance and a fixed reference $Z_0 \geq 6\Omega$ for internal matching). The layout selected for the JET ITER-like system, shown on Figure 1, consists of a fixed and an adjustable stage. No section of the circuit actually requires the lowest reference impedance Z_0 , as the antenna matching capacitors are directly connected to an in-vessel 9.5 quarter-wave stage ($\lambda_0/4=1.765\text{m}$, the broad racetrack-shaped vacuum transmission line [1]). This section matches a 3Ω load at midband. It is followed by a fixed half-wave 30 section, partly in vessel and including the DCF window. At the end of this section is inserted a fixed $\lambda_0/4$ low-impedance (12Ω) stub, providing access for hydraulic and cooling circuits. These stub and line sections also play an active role in the RF transformer, and are designed for additional adaptation of a 3Ω load at the edges of the frequency band, Figure 3. As a bonus, the first stage also matches $Z_0=6\Omega$ at 33 and 52MHz (Fig.3, right). The design is completed by adjustable line stretcher and stub, to cancel the residual reflection of the fixed stage, and for which a set of reference settings will be obtained at the operating frequencies and Z_0 of interest. The combined stages therefore enable ideal impedance transformation over the operating domain.

3. SIMULATED BEHAVIOUR OF THE SYSTEM

From fast RF measurements on the JET A2 antennae, e.g. [6], the ELMs are known to induce very large increases of resistive antenna loading (factor of 4 commonly observed), and at the same time significant reactance decreases of up to $\sim 10\%$. A variety of reactive variations are observed, and at present the precise effect of the ELMs on the input impedance matrix of a coupled ICRH array is open to various interpretations. Until more detailed information becomes available from ongoing analysis, the system response to ELMs is investigated using independent variations of the array resistance and reactance matrices obtained from 3D simulations [7], and assessed against the above orders of magnitude (Figure 4). Even with asymmetries and cross-talk between straps included in the model, the tolerance of the system to realistic load increases is still manifest (assuming the reference ELM-free matched configuration has been reached). A sensitivity analysis, Figure 5, shows that a sub-millimeter accuracy on the capacitor settings (i.e. better than 1pF at 55MHz) is mandatory to achieve optimum VSWR performance. This specification should be met by the selected hydraulic capacitor actuators. Cross-talk is found to affect voltages and power balance between straps significantly, and to increase the complexity of the matching procedure.

CONCLUSIONS

Within demanding constraints, a flexible implementation has been worked out for the matching circuit of the JET ITER-like ICRF antenna that will enable its comprehensive investigation on

ITER-relevant ELMy H modes. Experimental information on the load perturbations due to ELMs and antenna impedance matrix from 3D simulations contribute to the realism of ongoing circuit modelling. The impact of cross-talk between straps on maximum performance and control is a serious concern under intensive assessment. Uncertainty remains on the array impedance matrix and its variations during ELMs, and only tests of the launcher in 2005 can provide a definitive answer on performance. Great care is required in meeting demanding accuracy goals, and in developing robust matching algorithms for the coupled array.

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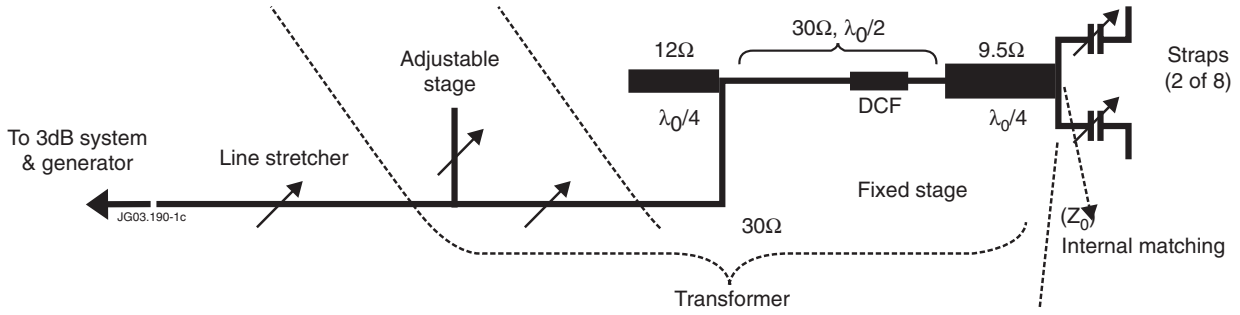
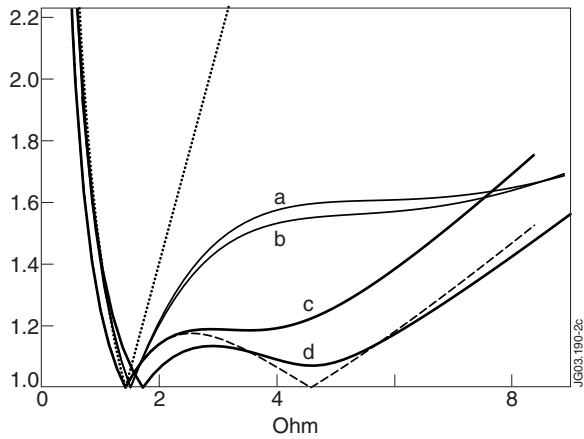


Figure 1: Schematic layout of transmission and matching circuit for one quarter of the JETITER-like antenna. Midband quarter wavelength: $\lambda_0/4=1.765\text{m}$. DCF: vacuum window. Z_0 : target reference impedance for internal matching.



Normalized branch resistance $r = R/Z_0$	Input VSWR	$\arg\left(\frac{I_2}{I_1}\right)$
0	∞	π
$S(1 - \sqrt{1 - 1/S^4})$	S	
$r_1 = 1 - \sqrt{1 - 1/S^2} = 1 - \cos \alpha$	1	$\pi - \alpha$
$x_1 = 1/S = \sin \alpha$	S	$\pi/2$
$r_2 = 1 + \sqrt{1 - 1/S^2} = 1 + \cos \alpha$	1	α
2		0
$S(1 + \sqrt{1 - 1/S^4})$	S	

Figure 2: Left: Input vswr versus branch input resistance (55MHz, $Z_0=3\Omega$). Dotted line: conventional matching circuit. Dashed line: ideal conjugate-T circuit (symmetrical branches, no mutual coupling between straps). More realistic models include nonsymmetrical straps (curves c, d) and mutual coupling (a, b). Curves a, c correspond to a top and curves b, d to a bottom antenna feed. Right: Ideal conjugate-T characteristic, relationships between matched loads (r_1, r_2), the vswr at local maximum (S), two other loads producing vswr S, and the relative phase between branch input currents.

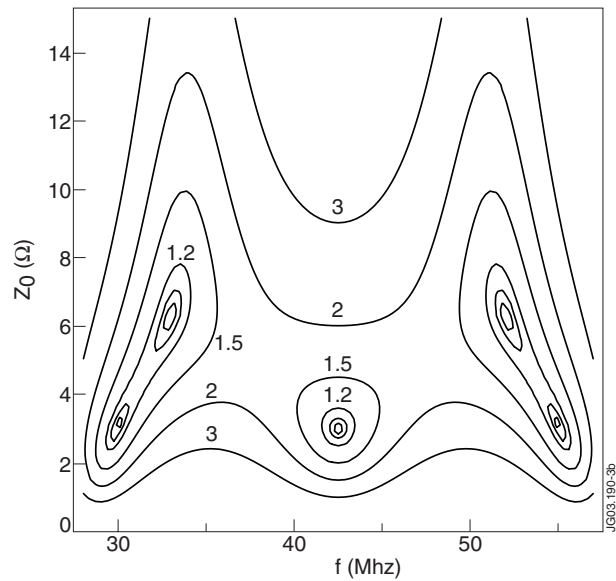
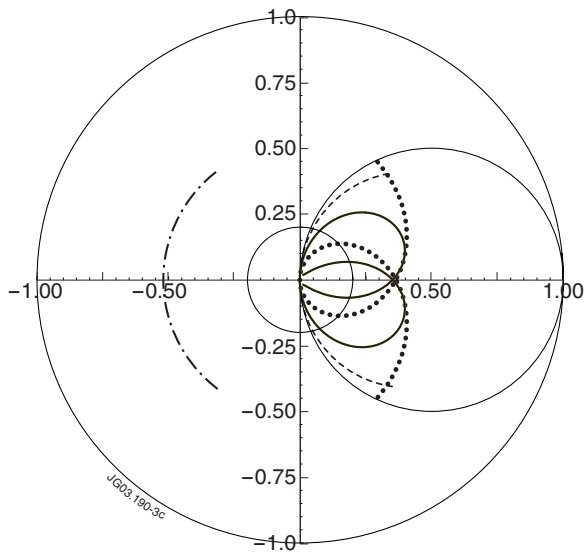


Figure 3: Design of the fixed transformer stage. Left: Smith impedance chart showing reflection at various points between 30 and 55MHz for $Z_0=3\Omega$. Dash-dots: end of 9.5Ω section; dashes: onto 30 section; dots: before service stub; thick continuous line: after service stub, showing 3 matched frequencies. Right: VSWR induced by the fixed stage versus frequency and Z_0 .

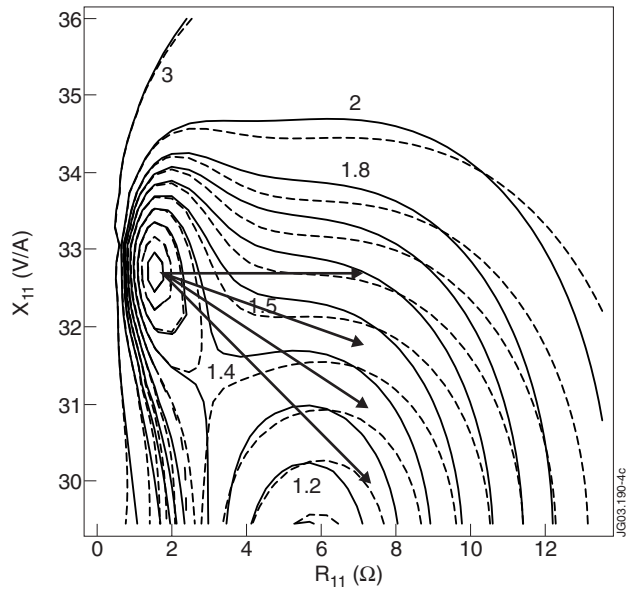


Figure 4: Input VSWR versus scalings of 4 by 4 resistance and reactance matrices (coupled array, toroidal dipole phasing). Plain / dashed lines: respectively top / bottom feed. Arrows indicate typical trajectories from reference match during ELM rise (55MHz, $Z_0=3\Omega$).

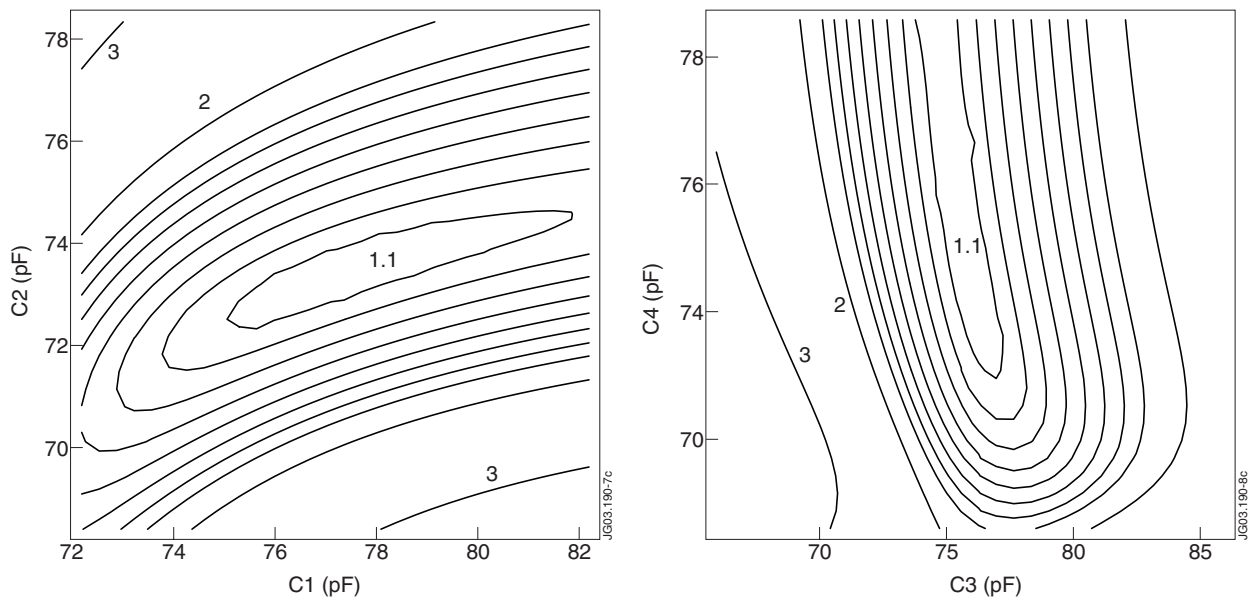


Figure 5: Input VSWR in the top feed line versus its two own capacitor settings (left, plot range 10pF), and versus settings of the capacitors of the bottom line (right, plot range 20pF).