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ABSTRACT.

The ITER-like ICRF Antenna for JET aims at validating novel antenna design principles in conditions as relevant as possible to ITER by coupling about 7.2MW to an ELMy H-mode plasma on JET in a frequency range from 30 to 55MHz. The power density, about 8MW/m^2, for a given maximum voltage in the circuit is maximized using poloidally short straps and the resilience to fast varying RF loads by matching pairs of straps by a so-called conjugate-T [1]. The paper reports the main characteristics of the final design as well as the main challenges encountered during the design and manufacturing phase of the key components.

1. MAIN DESIGN CHARACTERISTICS

The launcher (fig.1) is composed of four Resonant Double Loops, (RDLs), disposed in an array 2 toroidal by 2 poloidal. Each RDL consists of two polodially adjacent straps that are fed through invessel matching capacitors from a common Vacuum Transmission Line, VTL [2,3]. The matching consists of adjusting the matching capacitors such that the impedance at the common feed point, also referred to as the conjugate-T junction, matches a chosen matching impedance, Z_{CT}. In order for the circuit to exhibit resilience to mainly resistive load variations, Z_{CT} has to have a relatively low real part, typically between 3 and 6Ohms. Z_{CT}'s imaginary part can be chosen slightly different from 0, typically 1 to 1.5Ohm inductive, in order to compensate for the mutual coupling between the RDL's straps that could spoil its matching characteristics [8]. The impedance, Z_{CT}, is transformed to the characteristic impedance of the feeding main transmission lines and RF sources, 30Ohm, by a single stage quarter wave (at mid-band frequency) transformer, implemented by the VTL with a low characteristic impedance of 9Ohm, the quarter wave service stub and a phase-shifter-stub 2nd stage matching circuit (static but settings are function of frequency) [4]. The poloidally adjacent RDLs are fed from a 3dB hybrid splitter, by 4MW coming from combing two 2MW RF sources using a 3dB hybrid combiner (fig.2). The service stub allows bringing watercooling as well as hydraulic and electrical services to the in-vessel capacitors and their actuator systems. The 2nd stage matching circuit allows driving the conjugate-T junction with a real impedance between 2 and 7Ohm and a small imaginary part over nearly the whole of the frequency range. The phase-shifters in the main transmission line allow adjusting the phase between the two polodial RDL's fed in common: this is may further help the tweaking the coupled RDL RF characteristics and ease the demands on the matching algorithm to be developed.

The antenna strap feeders were optimised to reduce as much as possible the electrical field in the regions of highest voltage near the matching capacitors [5] and to make the current distribution along the circumference of its fixed electrode as uniform as possible. The electric fields are estimated to be about 2kV/mm for a coupling of 2Ohm/m at 55MHz. The operational domain (figure 3) is defined in the space antenna-coupling vs. frequency and shows the accessible coupling bounded by several constraints:

- The capacitor range, 80 to 300pF, mainly delimits the lower and upper frequency bounds: the limits shown do not take into account cross-coupling between RDLs and straps.

- The current through the matching capacitor, I_c, will delimit the maximum pulse length (scaling inversely with I_c^2) which is 10s or more for a capacitor current of 1480 A_{rms}. This pulse length limit pertains to the capacitor only and the thermal limits on the antenna straps are slightly lower and still need to be validated on the High Power Prototype (HPP). It is expected that 10s will be possible for currents up to 1250 A_{rms}.
- The feeder and capacitor voltages, resp. V_C and V_F, will delimit the lowest coupling reachable for a given voltage stand-off. The difference between maximum capacitor voltage and feeder voltages are small.

The tests on the High Power Prototype (ORNL and PPPL, US, fig.4) have confirmed the overall RF functional design of the single RDL [6,7] and the 3D RF modelling [5,Lamalle] was validated by measurements of the 2-port HPP antenna strap scattering matrix. A voltage stand-off of 45kV for short pulses was demonstrated, however for longer pulses issues related with the thermal stress in the antenna straps and antenna box sidewalls have become apparent. These stresses resulted in out gassing leading to breakdown or even meeting in the case of the antenna housing sidewalls. Many recommendations and actions for the final design and manufacturing of the JET-EP launcher have resulted from these tests and when feasible, the design of the various components involved was corrected in time for the start of their manufacturing phases.

2. MAIN CHALLENGES

2.1 DISRUPTION LOADS

The compatibility with worst case 6MA/4T plasmas disruptions on JET - taking into account assembly procedures and requirements for maintenance of the in-vessel matching capacitors - constituted one of the main mechanical challenges. The induced mechanical loads are mainly due to the plain copper cylinders and flanges of the matching capacitors located well inside the main toroidal magnetic field. These loads appear as torques about the axis of the capacitor's electrodes as well as perpendicular to it. Therefore, the design of the capacitors – Inner Vacuum Transmission Line (VTL) – RF Vacuum Window (VCW) system, has been modified from the original concept, in order to minimise and resist the EM induced forces. Design validation tests on mock-ups have also been carried out. In particular: the capacitor's OHFC copper to ceramic brazes have been reinforced; its outer envelope redesigned and copper partially replaced by SS; and the shaft of the variable electrode has been designed to be able to react the torque of about 600Nm induced on the electrode. After redesign, a torque of about 5kNm remains, which is reacted through the innerVTL by the RF vacuum window. In order to allow for this, the inner-VTL has been stiffened and the RF window increased in size. The VCW itself is of the double conical type with titanium inner- and outer conductors that was developed at JET. While this window is very strong mechanically and has a very good RF performance, its leads however to a challenging structural braze between Titanium and Inconel on the primary vacuum boundary. A prototype braze has recently been successfully achieved and work is ongoing to manufacture the first of a series of the VCW with this feature.

2.2. MATCHING ALGORITHM

One of the remaining challenges is the design of a matching algorithm that is able to take into account the complexity of the matching problem of several coupled RDL. Even for a simple RDL, and not taking into account the cross coupling between straps, the matching capacitors must be adjusted within a few tenths of mm in order to achieve the desired resilience to resistive load variations. Cross-coupling and load variations that may not be purely resistive further compound the issue [8], and a global solution is to be found that keeps the VSWR as low as 1.5 for real ELMs on JET. The present implementation with its second stage matching circuit allows to chose the impedance at the junction of the capacitors and improve the response of the launcher now taking into account realistic cross-coupling effects. RF circuit simulation is still on-going at present and the project aims at test matching algorithms on the testbed prior to installation on the JET torus by loading the antenna with an adequate “water load” [9].

2.3 ACTUATORS

The actuators positioning the matching capacitors will be based on servo hydraulics. Originally a solution based on vacuum-compatible electric motors was identified (and used on the HPP) but this had to be abandoned after the detailed calculation of the induced perturbation on the in-vessel magnetic field. Consequently, the layout of Antenna Pressurized Transmission Lines (APTL), that interface the main transmission lines with the RF vacuum windows, has been made compatible with the routing of cable and piping for the antenna in-vessel capacitors and servo-hydraulics components and instrumentation, and for secondary containment and vacuum inter-space monitoring services. Prototype testing in order to determine: minimum hydraulic pipe diameters; hydraulic fluid properties; and assess the accuracy of this system, has been carried out demonstrating accuracy in positioning well below 0.1mm and even below 50μm.

CONCLUSIONS

The manufacturing of the components of the antenna is underway. The results obtained on the High Power Prototype as well as the proof of principle test that was carried out using the A2 antennas [10] have validated the main RF design of the single RDL and have experimentally underpinned the underlying principles of load tolerant matching circuits. Robust matching solutions having been found numerically for a number of frequencies in the band, the most outstanding challenge remaining is the finding of a matching algorithm capable of coping with the complexity of cross-coupled RDLs.

The project has triggered unprecedented RF modelling of ICRF antennas (JET-EP as well as A2) with the most advanced tools available today. Based on this the installation and operation of the ITERlike antenna on JET will not only provide demonstration of ICRF coupling in ITER-relevant conditions but also provide a validation of modeling which will progress the understanding of RF coupling and matching of antenna arrays in fusion devices and allow optimizing the design of the ITER antenna itself.

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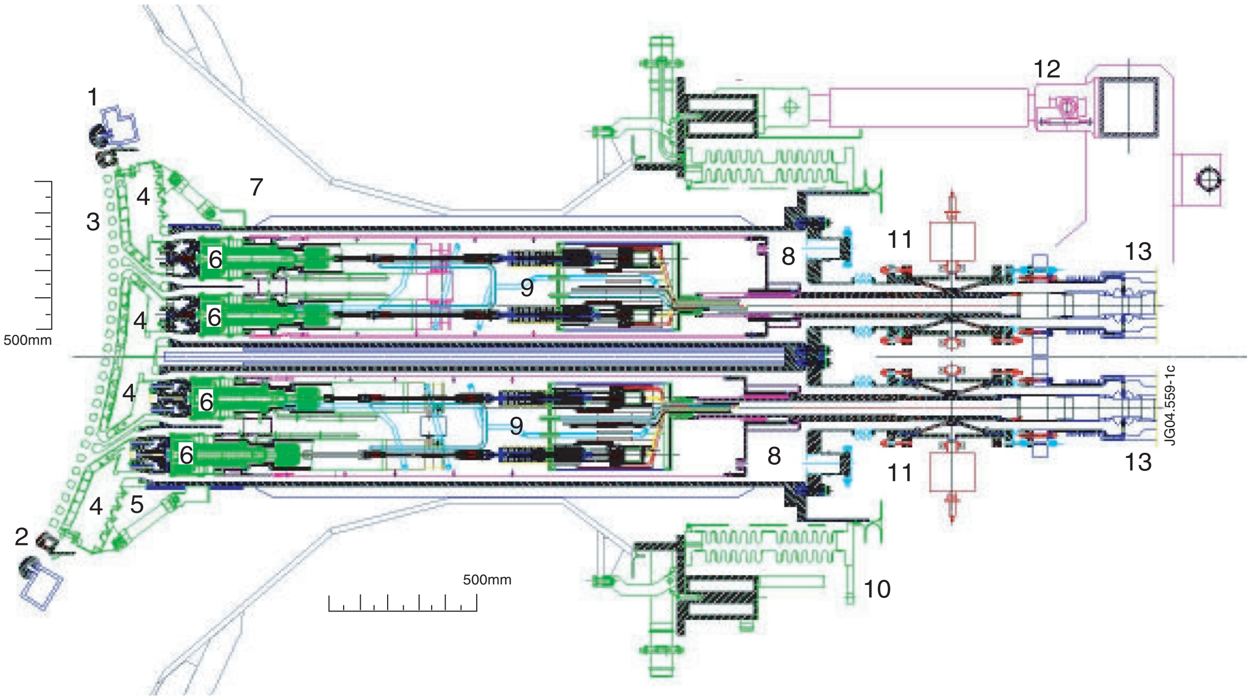
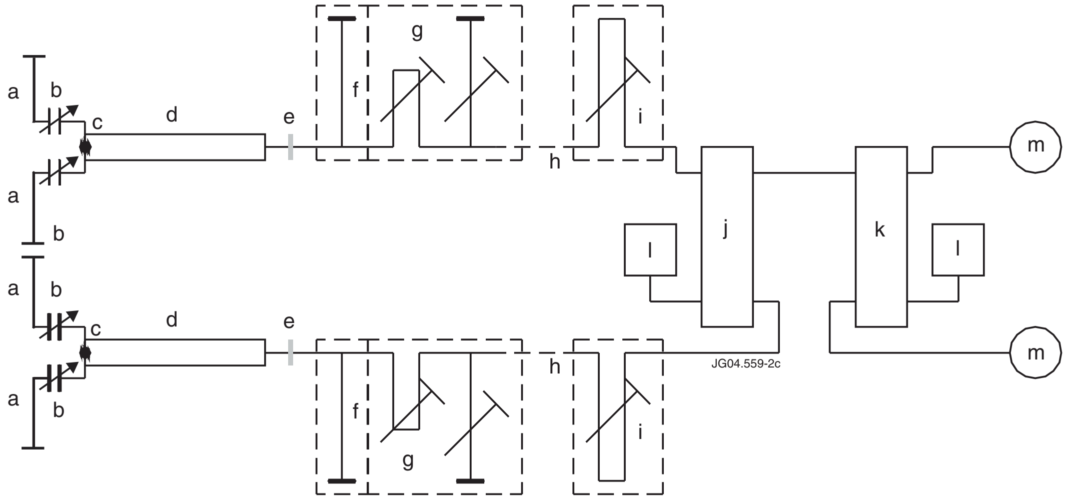


1. Main poloidal limiter,
2. Antenna private limiter,
3. Beryllium Faraday screen,
4. Antenna straps,
5. Antenna housing,
6. Matching capacitors,
7. Outer VTL and support box,
8. Inner VTL,
9. Actuator systems and drive rod mechanisms,
10. Main port bellows,
11. RF vacuum windows,
12. Ex-vessel support structure,
13. APTL (only partially shown)

Figure 1: Poloidal cut view showing one toroidal half of the antenna:



(a) antenna straps grounded in the antenna housing (not shown),
(b) matching capacitors,
(c) conjugate-t junction,
(d) quarter wave low impedance vtl,
(e) rf vacuum window,
(f) quarter wave service stub,
(g) 2nd stage matching circuit (phase-shifter / trombone),
(h) main transmission line,
(i) main trombone,
(j) 3dB hybrid splitter,
(k) 3dB hybrid combiner,
(l) dummy loads,
(m) 2MW rf source.

Figure 2: RF circuit diagram of one toroidal half of the antenna :

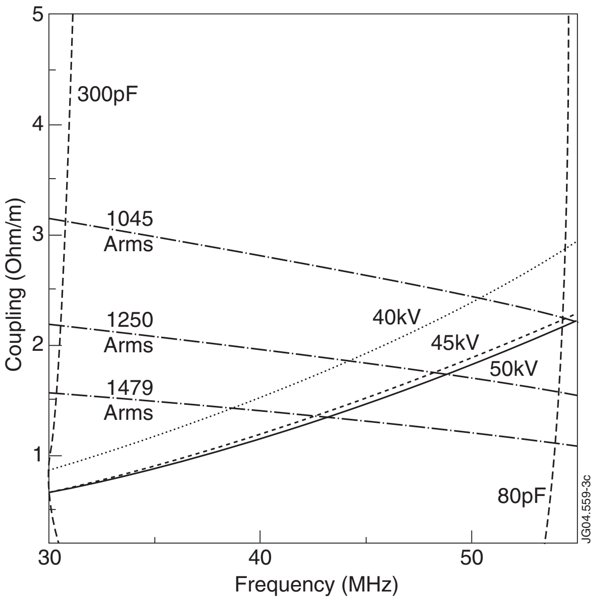


Figure 3: Operational domain bounded by the capacitor range (80 to 300 pF), Antenna strap and Capacitor currents (nominally 1250 Arms for 10s) and Capacitor and Feeder voltages (target 45kV).

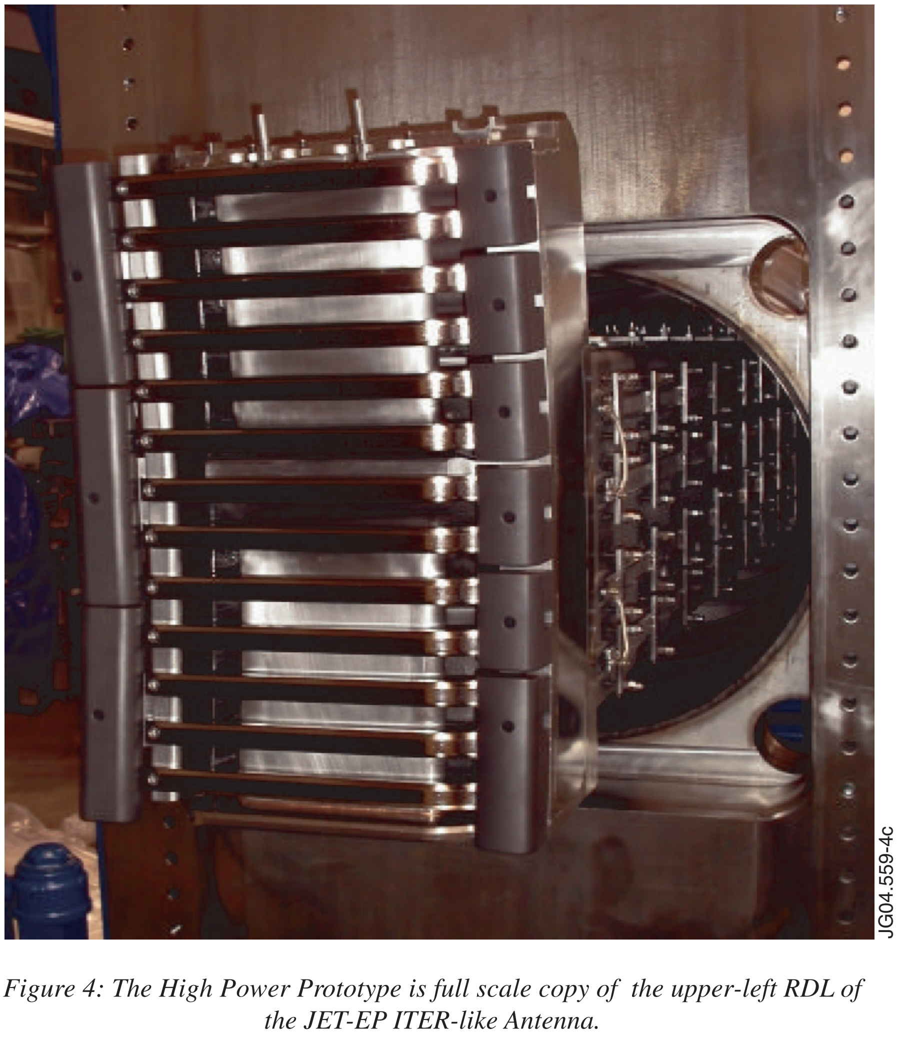


Figure 4: The High Power Prototype is full scale copy of the upper-left RDL of the JET-EP ITER-like Antenna.

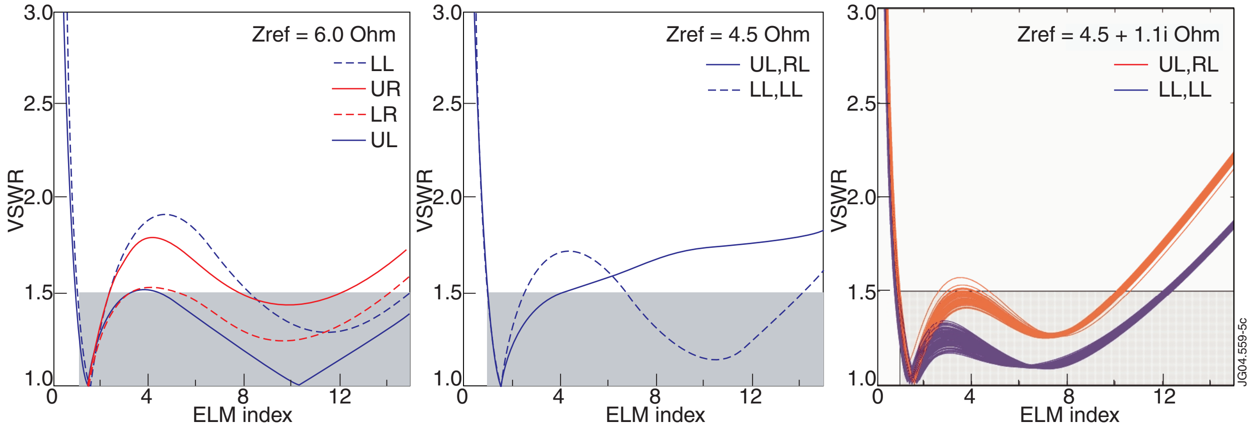


Figure 5: simulation of the VSWRs of the 4RDLs powered simultaneously at 54.5MHz during an ELM for different choices of the impedance, Z_{ref}, at the conjugate-T. The ELM is simulated as a (left) $Z_{ref} = 6\Omega$, in this case the most performing matching solution features non-symmetric values for the capacitors on the left and right side of the array, hence a different response for the 4RDLs to an ELM (additional asymmetries up/down due to the antenna straps). (middle) $Z_{ref} = 4.5\Omega$, in this case the most performing matching solution is symmetric and the performance in terms of ELM resilience is slightly improved. (right) $Z_{ref} = (4.5+ i\ 1.1)\Omega$ further improves the performance of the matching solutions. In order to assess its robustness, the capacitors have been perturbed simultaneously at random from their initial position by up to ±0.5pF corresponding to an actuator positioning error of about ±0.1mm. The matching values for the capacitors are given in the table below :

Table 1

RDL ⟶	Upper-Left (LL)		Lower-Left (LL)		Upper-Right (UR)		Lower-Right (LR)	
Z_{ref} (Ω)	C_1 (pF)	C_2 (pF)	C_3 (pF)	C_4 (pF)	C_5 (pF)	C_6 (pF)	C_7 (pF)	C_8 (pF)
6.0	68.00	117.25	103.00	66.75	84.00	72.75	74.50	94.50
4.5	148.00	73.75	74.75	112.00	148.00	73.75	74.75	112.00
4.5 + *i* 1.1	104.75	73.25	74.25	96.75	104.75	73.25	74.25	96.75

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