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ABSTRACT.
Following an overview of the ITER Ion Cyclotron Resonance Frequency (ICRF) system, the JET ITER-Like Antenna (ILA) will be described. The ILA was designed to test the following ITER issues: (a) reliable operation at power densities of order $8MW/m^2$ at voltages up to 45kV using a close-packed array of straps; (b) powering through ELMs using an internal (invacuum) conjugate-T junction; (c) protection from arcing in a conjugate-T configuration, using both existing and novel systems; and (d) resilience to disruption forces. ITER-relevant results have been achieved: operation at high coupled power density; control of the antenna matching elements in the presence of high inter-strap coupling, use of four conjugate-T systems (as would be used in ITER, should a conjugate-T approach be used); operation with RF voltages on the antenna structures up to 42kV; achievement of ELM tolerance with a conjugate-T configuration by operating at 3 real impedance at the conjugate-T point; and validation of arc detection systems on conjugate-T configurations in ELMy H-mode plasmas. The impact of these results on the predicted performance and design of the ITER antenna will be reviewed. In particular, the implications of the RF coupling measured on JET will be discussed.

1. INTRODUCTION

The ITER ICRF system [1], shown in Figure 1, will comprise two antennas provided by Europe, coupled to RF generators using transmission lines provided by India and USA respectively. The long term objective of this system is to couple 20MW/port into ELMy plasmas at an antenna strap-plasma separatrix spacing of approximately 17cm for pulse lengths up to 3600s at frequencies from 40MHz to 55MHz. This specification is particularly demanding for the antenna [2], in particular with respect to: coupling, voltage hold-off, matching, ELM tolerance, and thermal performance. A new antenna has therefore been designed for JET [3] to test developments in the first four issues. The results obtained using this new antenna and the resultant implications for ITER are discussed following an overview of the proposed ITER ICRF antenna.

2. THE ITER ICRF ANTENNA

Each ITER antenna will comprise a complete port plug which supports a closepacked array of 24 straps. It will be matched using components mounted outside of the torus (shown in Figure 2) that will allow powering through fast (sub-ms range) changes in loading during ELM's by the use of either 3dB couplers [4] or a conjugate-T configuration [5]. The present antenna design [2], shown in Figure 3, comprises a plug body that houses four RF power modules, each of which mounts six straps connected in triplets to two feed transmission lines, with protection provided by a series of Faraday screen bars. The rear section of each transmission line comprises a removable vacuum transmission line in order that RF windows and key diagnostics can be replaced from the rear of the port plug in the case of damage without the need to remove the entire plug. Much of the interior comprises shielding material to limit the activation dose at the rear of the port plug, and all port plug components are designed to survive the high thermal loads. All RF components are designed to operate at maximum RF voltage of 45kV, and the antenna includes RF diagnostics to provide the means of matching the antenna system and to provide arc protection.

Modelling of the coupling from the ITER antenna has been carried out using ITER edge density profiles provided by Loarte [6] and two RF codes: TOPICA [7] and ANTITER II [8]. Coupled powers of order 12-20MW/antenna have been predicted [8] and Figure 4 shows the predicted coupling [9] using the “baseline” Sc2 short 17 (ITER scenario 2 15MA inductive scenario Q=10 with short SOL of outward pinch velocity of 30m/s) ITER edge conditions with the antenna operated at 45kV on a pure D plasma heated at second harmonic at five antenna phasings.

3. THE JET ITER-LIKE ANTENNA (ILA)

Over the last seven years, a major project has been undertaken by EU associations and EFDA-JET CSU to provide an additional JET antenna. The ILA, shown in Figure 5, was designed to couple 7.2MW (8MW/m2) across the frequency range 30-55MHz, using a close-packed array of low-inductance straps mounted as four Resonant Double Loops (RDL’s), each consisting of two poloidally adjacent straps, arranged in a 2 toroidal by 2 poloidal array. ELM tolerance is incorporated using an internal conjugate-T junction with each strap fed through in-vessel matching capacitors from a common vacuum transmission line. Key features of this antenna are protection during low-voltage arcing in a conjugate-T configuration, using both existing and novel systems; and resilience to disruption forces. Key objectives were to: operate at high power density; test ELM tolerance; and measure the coupling at ITER relevant plasma-antenna spacing. The antenna was installed onto JET during 2007 and has operated from May 2008. As the ILA design was frozen in 2003, it does not fully match the current ITER antenna design. In particular, the ITER antenna: does not use in-vessel matching (capacitors); does not use a conjugate-T configuration (but could do so, if required); requires high RF voltages and electric fields throughout the antenna; connects straps together in triplets; and uses decouplers within its matching system to reduce the effect of first order mutual coupling between straps. The basic strap configuration, however, remains unchanged (except in minor dimensional issues), and the conclusions from the JET ILA regarding coupling and ELM tolerance discussed below remain relevant.

4. KEY ILA RESULTS AND THEIR RELEVANCE TO ITER

The full results from this antenna have been described by Durodié [10], [11]. The key ITER-relevant conclusions are:

- Antenna RF voltages up to 42kV were achieved routinely on both the RF test bed and JET. *The choice of 45kV for ITER appears sound*, with the caveat that the design of the ILA limits the regions exposed to high voltages (peak voltages on the ITER antenna can apply further back into the antenna structure).
- Operation at ITER-relevant power densities was achieved.
- Control of the antenna matching elements in the presence of high mutual coupling between

straps using four conjugate-T systems (as will be used in ITER, should the conjugate-T approach be used) proved feasible (but did require several developments of the matching system). *The ITER-relevant use of a high power density conjugate-T configuration was confirmed.*

- *ELM tolerance with a conjugate-T configuration was achieved* by operating at 3Ω real impedance at the conjugate-T point.
- Validation of arc detection systems on conjugate-T configurations in ELMy Hmode plasmas was carried out [12] and [13]. The Scattering Matrix system (SMAD) operated successfully and the Sub-Harmonic system (SHAD) proved to be efficient, after tuning of the system sensitivity, and should offer extra protection in some conditions.

The main issue of concern for ITER was the low value of the coupling (0.8Ω/m) measured in H-mode for the ILA on JET. This is lower than originally anticipated as 1.5Ω/m was expected at increased ROG (separatrix to first wall spacing) and appears to contradict the values required for achieving 20MW per antenna on ITER (especially given the much higher spacing between the separatrix and the first wall expected for ITER). This is discussed below.

4. DISCUSSION OF THE MEASURED JET ILA COUPLING

In order to assess the implications of the measured coupling for ITER, two additional analyses have been carried out, using the data shown in Figure 6.

Firstly, the use of TOPICA for predicting the coupled power of high power density strap arrays has been tested by modelling of JET Pulse No: 77852. This is an ILA 42MHz upper half only pulse (to reduce errors in the way TOPICA models the antenna to plasma edge distance for a full curved antenna [7]) in which the ROG was varied from 4 to 8cm as shown in Figure 6. The power coupled to the plasma can be most conveniently expressed in terms of the RF quantities "effective conductance" G_{eff} (at the RF probe fixed capacitor flange position), and/or the historically better known "effective strap resistance per unit length" R'_{eff} defined in terms of coupler powers and strap currents/voltages by

$$G_{eff} = \frac{2\,\mathrm{Re}(P^{+}_{couplers})}{V^2_{capacitor1} + V^2_{capacitor2}} \quad and\ R'_{eff} \approx \frac{\mathrm{Re}\ P^{+}_{couplers})}{|I_{strap1}|^2 + |I_{strap2}|^2}\left[\frac{}{I_{strap1} + I_{strap2}}\right]$$

G_{eff} has the advantage that it can be directly obtained from the scalar directional coupler and RF probe measurements only. R'_{eff} starts from the full amplitude and phase data, and involves complex calculations with an approximate transmission line model and is thus more error prone. The coupling calculated from the TOPICA data is shown for two possible matching solutions (Z_T = 3 – jX and 3 + jX) as final confirmation of which theoretical coupling applies to the measurement (depends on direction of toroidal fields, currents, poloidal spectrum) awaits further experimental verification.

Representative error bars are shown of ±1cm on position and ±21% on power; the errors due to the RF modelling of R'_{eff} are assumed to be small. Good agreement is seen within error bars, especially for G_{eff}. This appears to validate TOPICA, which agrees with earlier validation on Tore Supra [15], DIIID [16] and Alcator-C [7].

A second simple 1D scaling model uses the coupling measured on the ILA for the L-mode Pulse No: 77852 at low separatrix to first wall spacing discussed above (1.48 /m) to predict that expected for the ITER antenna. The antenna spectra [9] and SOL density profiles ([6] for ITER and Figure 9 for JET) have been used to predict the cutoff density positions (relative to the strap front face) shown in Table 1. Note that two data values are included for the ITER dipole (0,π,0,π) case as this spectrum exhibits a significant secondary peak at low k//, which is taken into account in the scaling.

Table 1 shows the surprising observation that *the spacing between the antenna straps and cut-off positions is of similar magnitude on JET (low antenna/plasma spacing) and ITER*, despite the much larger separatrix to first wall spacing on ITER (17cm compared to 4cm). Figure 8 shows the resultant coupling predicted for the ITER antenna for the baseline sc2 short 17 edge for all relevant antenna phasings, assuming that the coupling is scaled by the relative tunneling factor $exp(-\alpha \pm k_{//}dc)$, where dc is the strap to cut-off spacing and α is the tunneling factor (2 for a hard edged plasma and 1.1 for a linear density ramp [14]). Figure 8 compares the results for R′ predicted using ANTITER II plus the JET data scaled for three values of α. The results show a good level of agreement especially at a tunneling factor of 1.5.

The remaining question is then the use of L-mode data for scaling to an H-mode plasma, which exhibits lower coupling on machines such as JET due to the effects of increased density gradients close to the plasma edge. This particular issue has been assessed using the density profiles shown in Figure 9 for: the JET L-mode (Pulse No: 77852 4cm separatrix to first wall spacing); a representative JET H-mode shot (Pulse No: 77851, whose absolute position relative to the strap face has not been confirmed) and the ITER sc2 short 17 edge. This shows the second key observation: *the density gradients for the ITER edge are (a) of similar magnitude close to the cut-off position to that of the JET L-mode (approximately $10^{20}m^{-4}$) and (b) the position where the ITER Hmode density gradient becomes high (approximately $2\times10^{20}m^{-4}$) lies 10cm inboard of the cut-off position, where its effect on coupling will be significantly reduced by the increased SOL density at that position*. Given these observations, the variations in coupling due to density gradients are assumed to be small and tunneling is assumed to dominate the coupling scaling. Note that the TOPICA and ANTITER II antenna models include the high density gradient regions; effects due to gradients have therefore been included within the predicted powers and coupling in [8,9].

Despite the approximate nature of such scaling, it shows that the coupling achieved in L-mode at low separatrix to first wall spacing using the JET ILA is consistent with that predicted for the ITER antenna by TOPICA and ANTITER, providing the ITER edge densities provided by Loarte and used for both TOPICA modeling and the scaling analysis will be achieved on ITER.

CONCLUSIONS

The ITER ICRF system is presently being designed by IO and the Indian, US and EU Domestic Agencies to meet a 20MW ELM-tolerant specification. An ITER-Like Antenna (ILA), constructed for JET to test coupling on ELMy plasmas using an ITERrelevant strap design in a conjugate-T configuration, has shown that such antennas can operate at ITER-relevant voltages and achieve simultaneous high power density and ELM tolerance. The key concern arising from this antenna has been lower coupling on H-mode plasmas than expected. JET L-mode data has been used to show that: (a) the code TOPICA used as the main predictive tool for the ITER antenna coupling correctly predicts the JET antenna performance; and (b) the coupling predicted for ITER H-mode plasmas is consistent with that measured on JET.

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Machine/Phasing	**$k_{\|\|}(m^{-1})$**	**$n_{ecut\text{-}off}\,(10^{18}\,m^{-3})$**	**Strap to Cut-Off Distance d_c (cm)**			
JET 0,π	6.7	2.45	8.4			
		ITER Edge:	**Sc2 short**	**Sc4 short**	**Sc4 long**	**Sc2 long**
ITER 0,π,0,π	7.5	2.88	11.5	13.9	10.2	6.9
	2.1	0.16	7.2	7.7	–	–
ITER 0,0,π,π	3.0	0.40	8.3	9.1	–	–
ITER 0,π,π,0	4.5	0.99	9.5	10.7	5.7	–
ITER 0,π/2,π,3π/2	3.6	0.61	8.8	9.7	4.7	–
ITER 0,−π/2,−π,−3π/2	3.8	0.69	9.0	9.9	4.8	–

Table 1: Comparison of the cut-off density positions for the JET ILA and ITER antennas (Cases with no distance listed have the density at the first wall above cut-off).

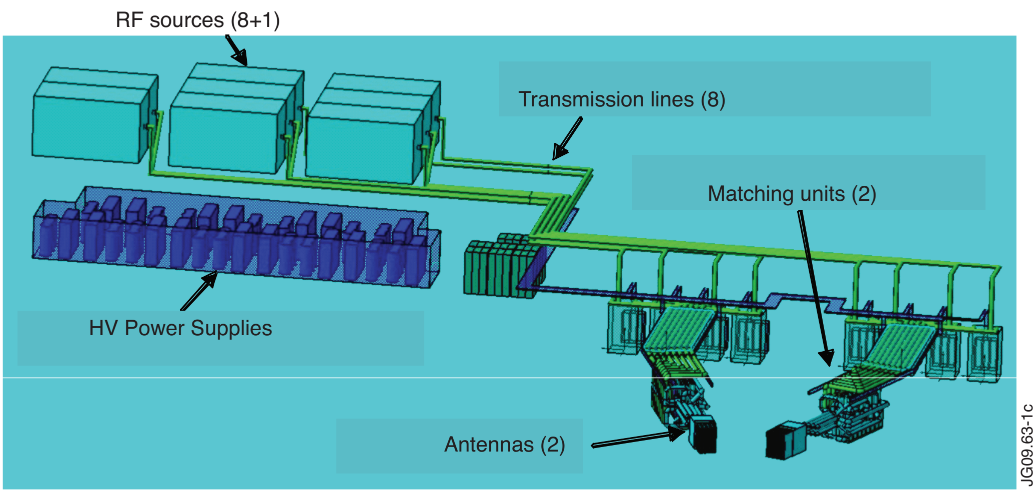


Figure 1: Schematic of the Present Baseline ITER ICRF System.

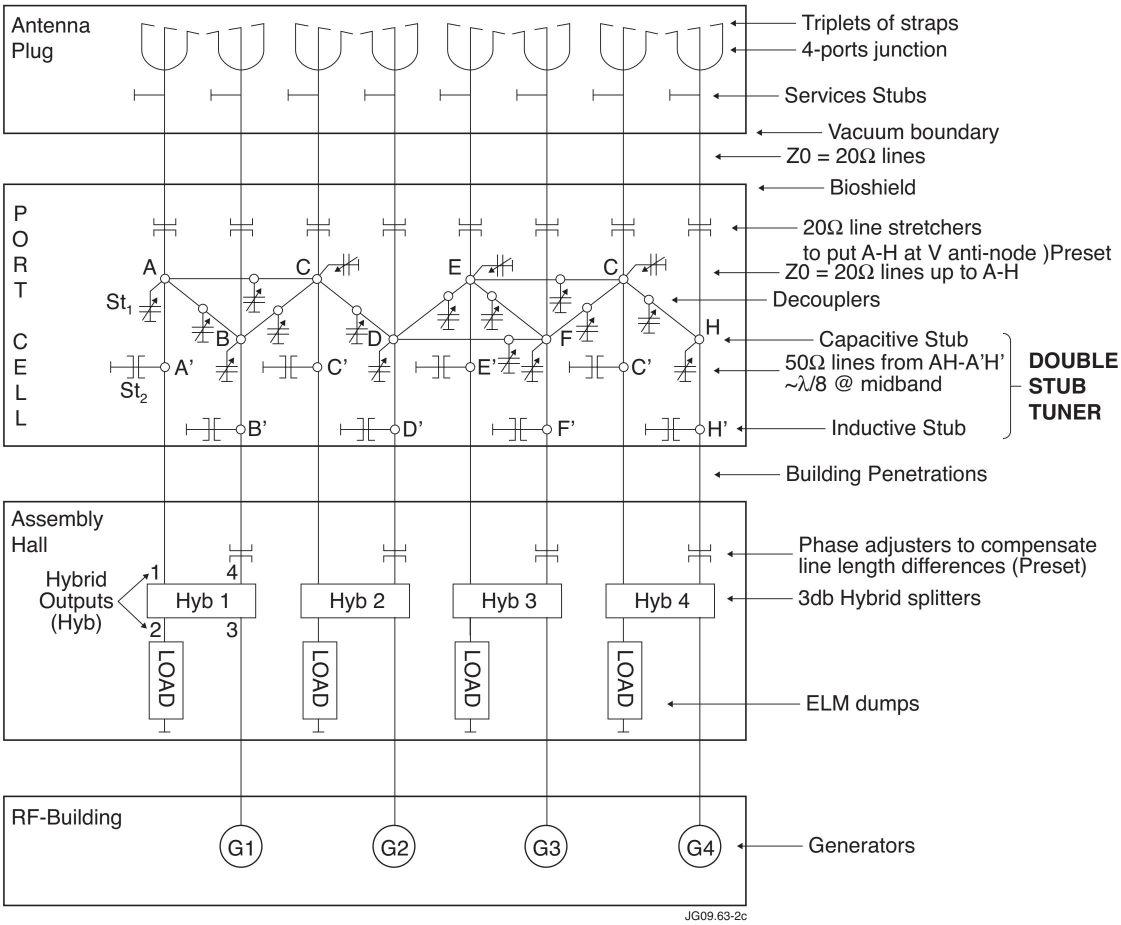


Figure 2: ITER ICRF Matching System Layout.

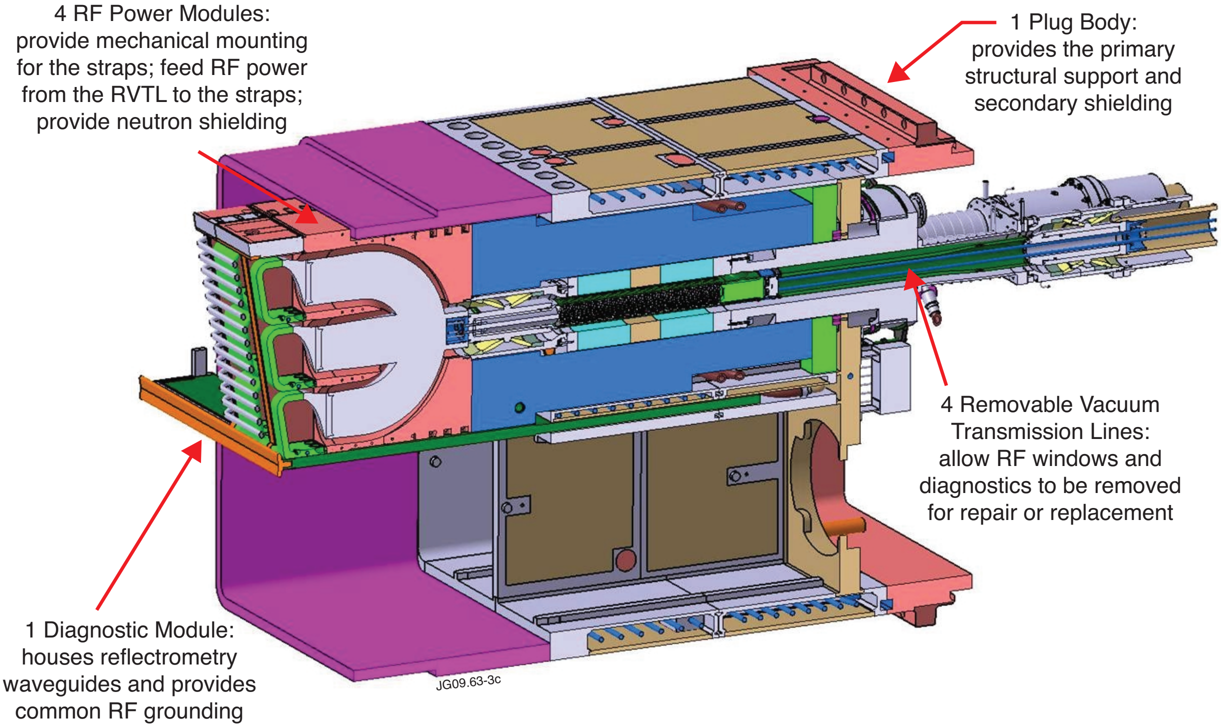


Figure 3: CATIA Model of the ITER Antenna Port Plug (Fitted with One of Four RF Power Modules).

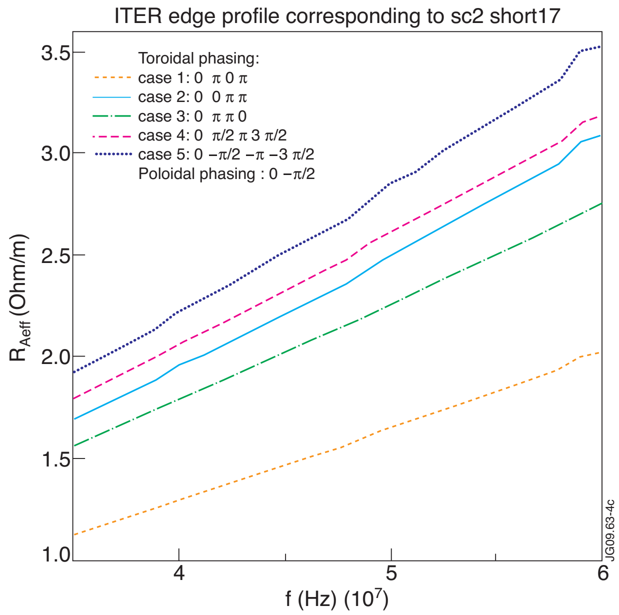
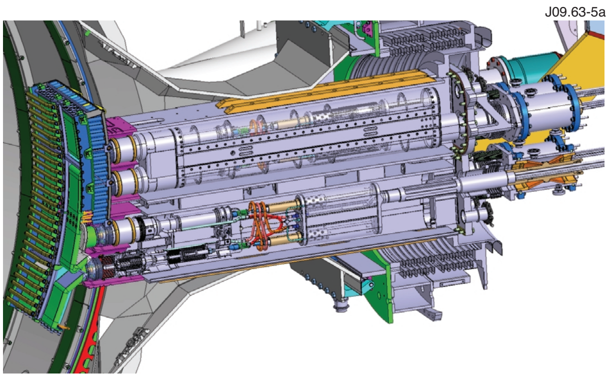
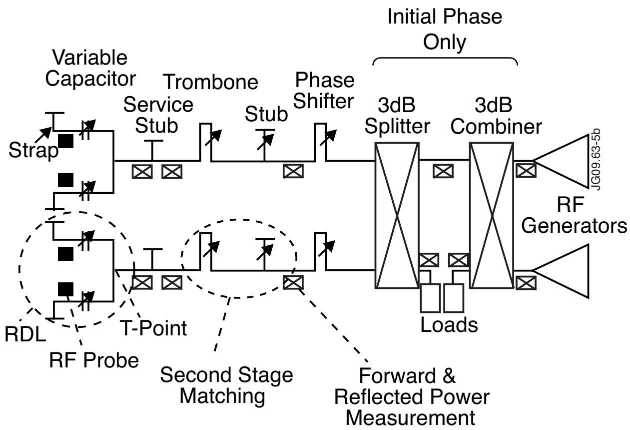


Figure 4: Predicted ITER Coupling [9].



(a) Isometric view



(b) Equivalent circuit

Figure 5: The JET ILA.

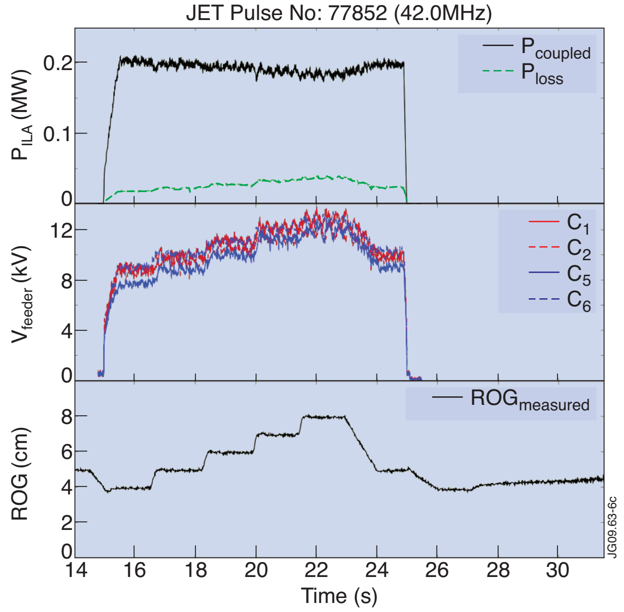


Figure 6: ILA Performance on JET Pulse No: 77852: (a) Power; (b) Strap Voltage; (c) ROG (Separatrix to First Wall Spacing)

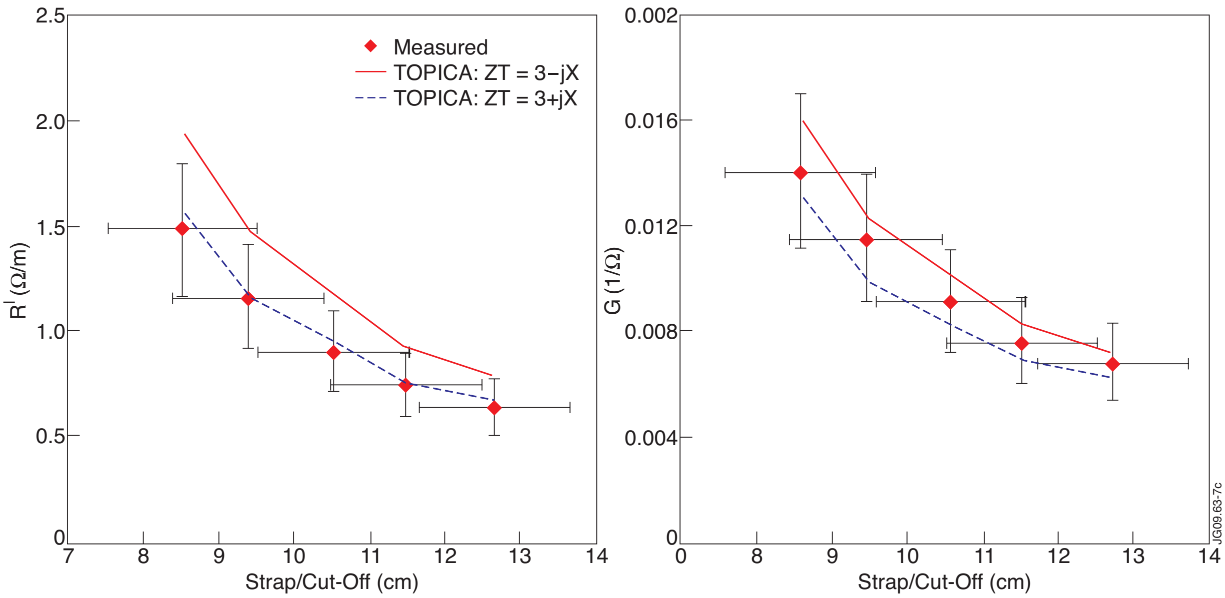


Figure 7: Coupling Predicted for the JET ILA Using TOPICA L-mode

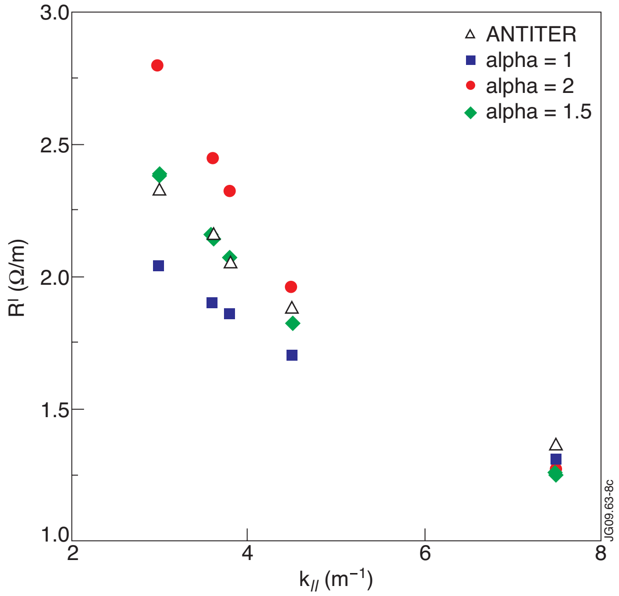


Figure 8: Coupling scaling from JET L-mode data to the ITER H-mode (sc2 short 17 edge).

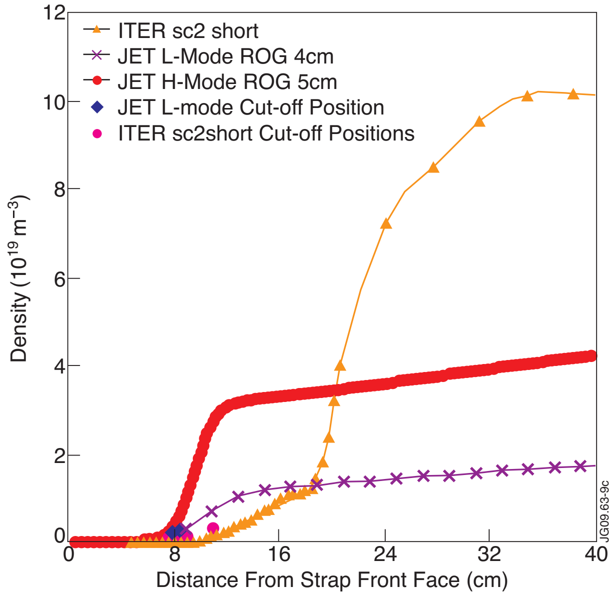


Figure 9: SOL density profiles for JET and ITER cases