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RF and Mechanical Design of the ITER Ion Cyclotron Resonance Frequency Antenna

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Abstract. The ITER Ion Cyclotron Resonance Frequency (ICRF) antenna is required to couple 20MW through fast (sub-ms) changes in loading during Edge Localised Modes (ELM's). The chosen design comprises a port plug supporting a close-packed array of 24 straps which are connected in triplets to eight transmission lines fed via 3dB couplers or a conjugate-T configuration. Significant RF engineering challenges have arisen given the need to maximise the coupled power and/or reduce electric field strength for the straps, feeders and transmission lines, whilst minimising power loadings caused by sheath effects. For instance, the use of closely-spaced straps leads to significant levels of inter-strap mutual coupling that complicates the matching algorithm, calling for external decoupling networks. Arc detection is also a key issue for this antenna, as recent JET and Tore Supra results have highlighted the need for parallel development of arc detection and ELM-tolerant systems. The mechanical design challenges lie even further beyond the range of present experience. The limited space available, coupled to the requirements that the RF components are sufficiently large to achieve acceptable electric field levels, and the need to provide adequate neutron shielding throughout the port plug, leads to a complex mechanical layout. Achieving a port plug design that can survive the high thermal loads and be resilient to disruption forces significantly complicates the design. This paper details the RF and mechanical design features proposed for the antenna and outlines the manner in which the wider EU programme will feed into the design process.

1. Introduction

The antenna for the ITER ICRF system [1],[2], which is to be provided by Europe, needs to couple 20MW at ITER-relevant antenna strap-plasma separatrix spacing (approximately 18cm or more) for pulse lengths up to 1000s at frequencies from 40MHz to 55MHz. It will be matched using components mounted outside of the torus that will allow powering through fast (sub-ms range) changes in loading during ELM's by the use of either 3dB couplers or a conjugate-T configuration [2]. This paper details the RF and mechanical design features being considered by the present EU antenna design team for the antenna. *Note that the conceptual design phase is presently in progress and so the design shown below is a snapshot of that presently being considered by the design team; this design will continue to evolve until fixed in consultation with ITER and the ITER EU Domestic Agency F4E.*

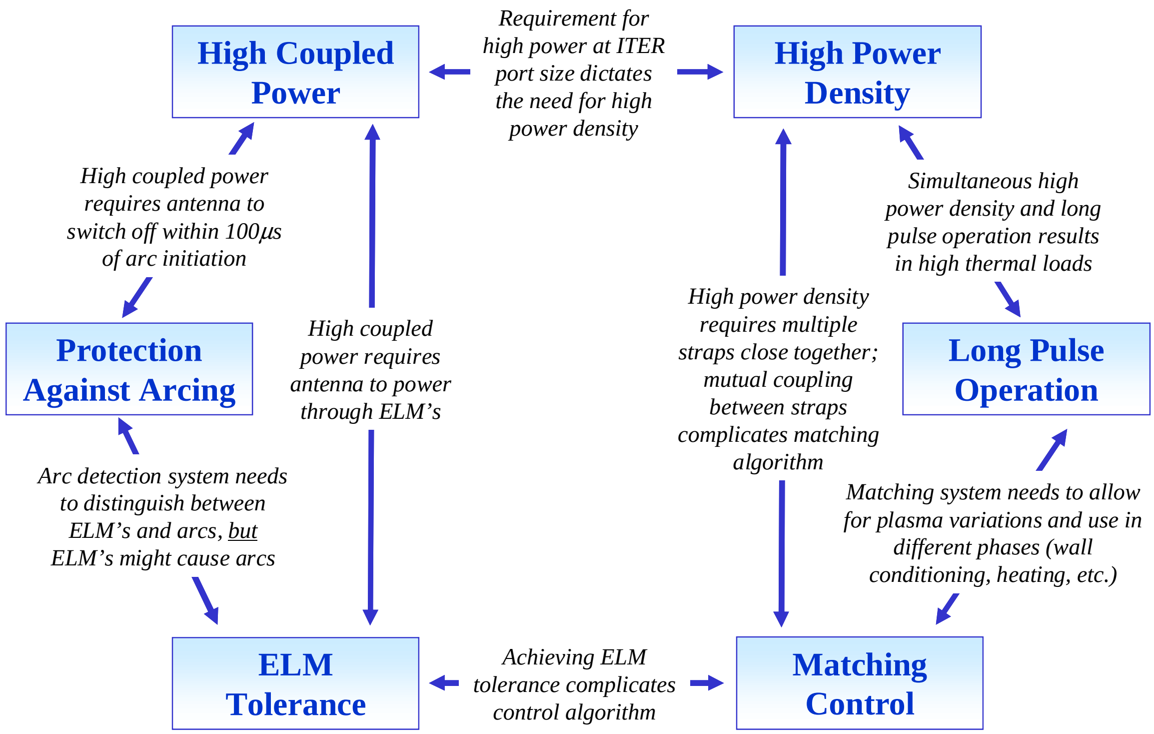

FIG. 1. Key Design Issues for the ITER ICRF Antenna.

2. Key Design Issues

A number of key design issues provide substantial challenges in establishing a conceptual design. These are summarised in Figure 1, which shows their inter-related nature. In many of these areas, the design will need to achieve substantial progress beyond existing operational antennas. In particular, being able to match into ELMy plasmas with the antenna operated at high power density represents a major RF step beyond large antenna systems to date, and is the rationale for new antenna designs that have recently been tested on Tore Supra [3] and JET [4]. No less challenging are the mechanical engineering requirements for operation with high heat fluxes and for long pulse lengths.

3. Present Baseline ITER ICRH Antenna Design

The present antenna design, which is shown in Figures 2, 3 and 4, comprises a port plug that houses four RF Power Modules, each of which mounts six straps connected in triplets to eight feed transmission lines, with protection provided by a series of Faraday screen bars. The rear section of each transmission line forms a Removable Vacuum Transmission Line in order that RF windows and key diagnostics can be replaceable 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. The design includes RF diagnostics to provide the means of matching the antenna system and to provide arc protection.

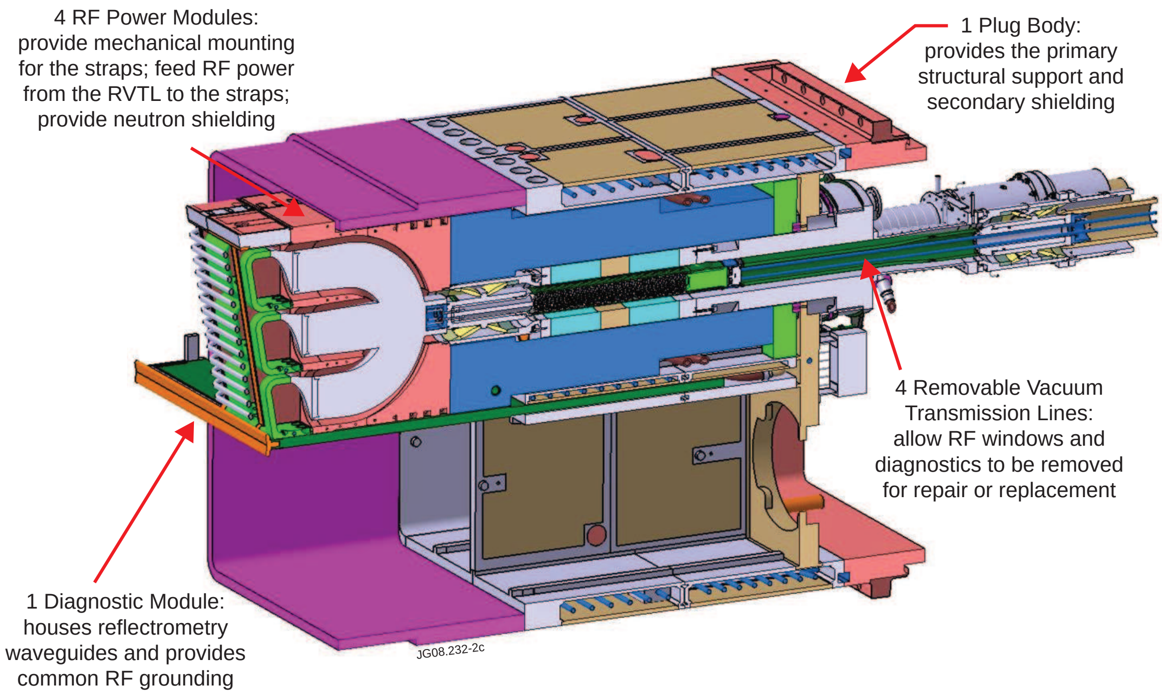

FIG. 2. Section through the ITER ICRF Antenna with one RF Power Module (and RVTL) Installed.

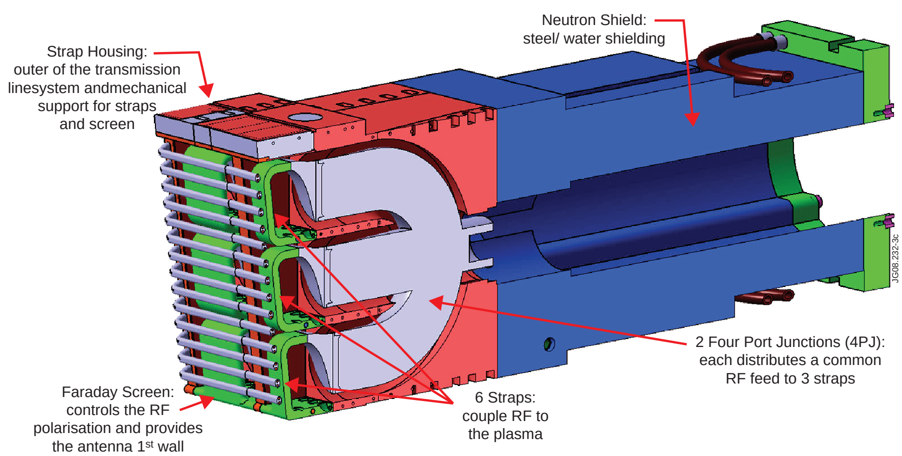

FIG. 3. Section through one RF Power Module (RVTL Removed).

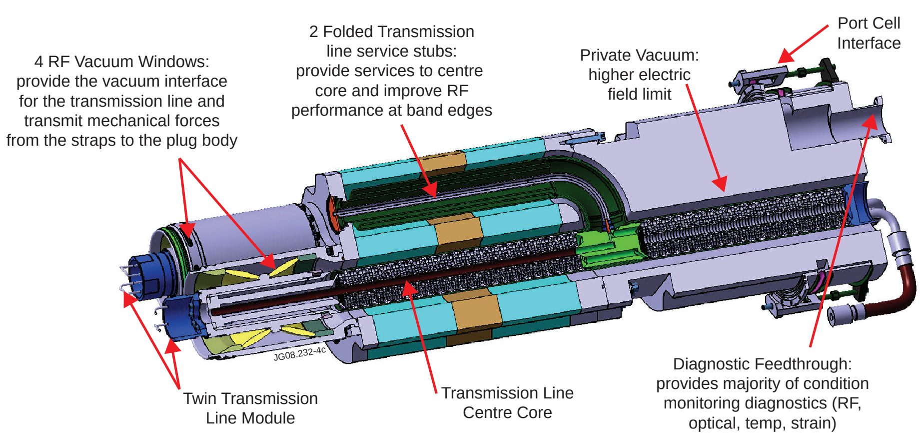

FIG. 4. Section through one Removable Vacuum Transmission Line (RVTL).

4. RF Design

The design of the proposed matching system, which now lies outside of the antenna port plug, is discussed in detail by Dumortier et al [5]. Key RF design issues for the antenna design team are: optimisation of the design to achieve the 20MW specification at acceptable RF voltages within the antenna; achieving an antenna grounding design that avoids excessive RF voltages appearing in the surrounding ITER systems and minimises power loadings arising from RF sheaths; and integrating the diagnostics required to operate, match and protect the antenna.

4.1. Coupling

The antenna-plasma spacing of order 15cm makes the coupling of 20MW difficult at achievable levels of peak electric field within the antenna (<1.5kV/mm within regions exposed to torus vacuum; <3kV/mm in private vacuum). To tackle this problem, the antenna uses a close-packed array of straps to achieve the required power density of 8-10MW/m^2, which leads to significant levels of inter-strap mutual coupling that are, to lowest order, externally compensated by reactive de-couplers. This mutual coupling significantly complicates the matching algorithm, but can be controlled by the design of the vertical septa positioned between adjacent straps, leading to a trade-off as reduced mutual coupling leads to both easier matching but decreased maximum power coupled to plasma. A key element of the present design process, therefore, is the use of modelling to optimise the design of straps, feeders, housing and transmission lines to maximise the coupled power and/or reduce electric field strength. Studies using the 3D code CST Microwave Studio and transmission line theory have been discussed by Dumortier et al [6], and are summarised in Figure 5, where the various curves indicate specific designs considered as part of the optimisation (compared to the October 2007 reference design). The results show that the estimated coupled power has increased across the entire frequency range of interest by values of up to 165%. In addition, the computer code TOPICA [7], which has been used for predicting coupled power for the ITER-like antennas for JET [4] and Tore Supra [8], has been used to estimate the coupled power and to feed into an assessment of power loadings arising from sheath effects. Figure 6 shows a typical result, assuming the case of the plasma with 17cm gap and short decay length (see [9] for scrape-off layer details). The resultant coupled power suggests that the 20MW can be achievable; dependant on plasma edge scenario.

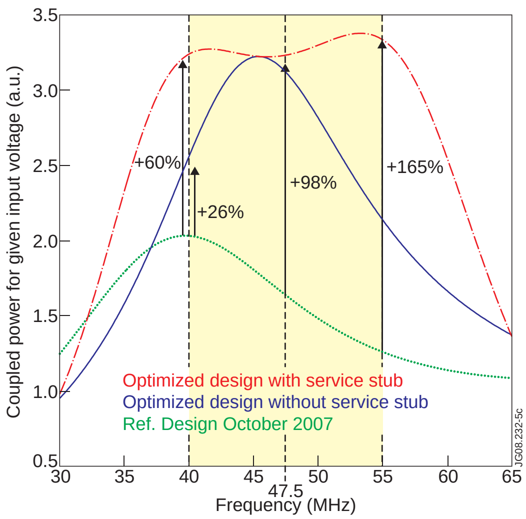

FIG. 5. Summary of 2008 Antenna Optimisation [6].

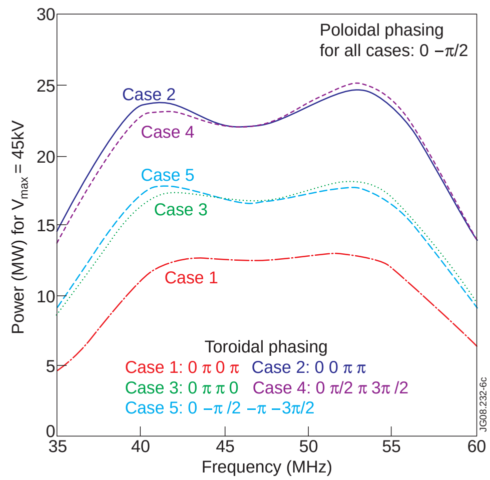

FIG. 6. Coupled Power Predicted by TOPICA (Maximum RF Voltage = 45kV; plasma scrape-off layer: Sc2 17).

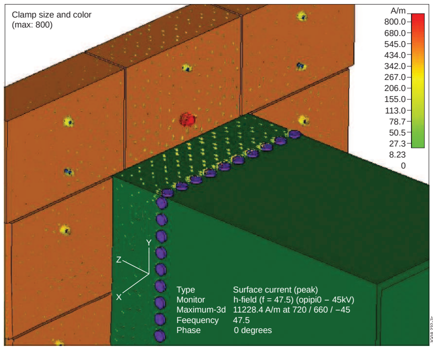

FIG. 7. MWS model. Rear view of the current distribution on the port plug surface (green), blanket modules (orange), blanket connectors (red and yellow). In mauve: grounding discs.

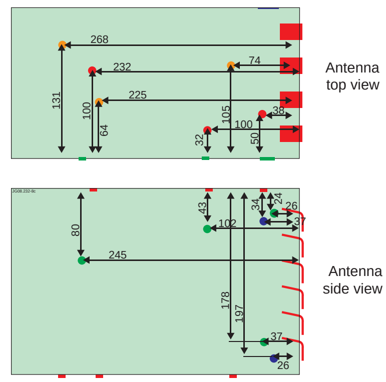

FIG. 8. HFSS model. Location of the grounding discs on the port plug surface (coloured circles). Antenna straps are shown in red.

4.2. Grounding and RF Sheath Effects

Two inter-related antenna physics issues are the need to avoid high electric fields generated at resonances of the gap-cavity around the port plug and the requirement to minimize power loadings that can strike key components within ITER due to the acceleration of plasma particles by rectified plasma sheaths resulting from RF fields. Resonances of the gap-cavity have been computed with Microwave Studio (MWS) and HFSS. A limited number of grounding locations have been proposed that suppress all major resonances and either minimise connector currents or cover higher harmonic range, as shown respectively in figures 7 and 8 from recent unpublished modelling carried out by Louche et al and Braun. TOPICA modelling is now being used also to predict and minimise RF voltages and the power loadings caused by sheath effects.

Colas et al [9] have recently proposed that significant power densities can arise from sheath effects for the chosen antenna geometry; dependant on the assumption for edge plasma and neutral parameters. This modelling now needs to be fully integrated into a combined model for grounding (which strongly affects the RF sheath voltages) and the edge model to be adopted for ITER design purposes.

4.3. Antenna RF Diagnostics

Arc detection is a key RF issue for this antenna, as recent results on Tore Supra [3] and JET [4] have highlighted the need for parallel development of arc detection and ELM-tolerant systems. It is presently proposed that 32 RF voltage probes and 48 optical arc detectors are required within the antenna to allow control of the antenna matching and to protect against damage from arcing and over-voltage. In addition, RF diagnostics will be used throughout the transmission line system to allow control of the matching.

An additional requirement is the incorporation of reflectometry into the antenna, given the dependence of coupling on the density profile in front of the antenna. Of primary importance are the position of the fast wave cut-off, which determines the amount of wave tunnelling in the evanescent region, and the sharpness of the density gradient, which will cause additional wave reflection. It is important to have the density measured in front of the antenna because (a) density profiles up to the far scrape-off layer will not be toroidally and poloidally uniform and (b) the RF power itself may change the density through ponderomotive forces and **E**×**B** drifts generated by sheath voltages. The latter are, in turn, dependent on the scrape off density near the antenna. These drifts may generate convective cells in front of the antenna that break the poloidal symmetry of the density. In addition, the antenna-LCFS distance also varies poloidally. Therefore, it would also be desirable to have the density profile measured at different poloidal locations. Incorporation of one or more reflectometry systems into the antenna is under consideration at present.

5. Mechanical Engineering Issues

The combination of mechanical loads, long pulse length and geometrical limitations produce mechanical design challenges that lie well beyond the range of present ICRF experience.

5.1. Geometric Issues

Space is heavily constrained within the antenna, given the conflicting requirements that the port plug must fit within the allowed space whilst electric fields must not rise above target values. The requirement that the rear transmission line section is removable considerably increases the complexity of the mechanical layout. Further RF and mechanical issues arose during 2007 with the requests that the antenna should be capable of limited adjustment during shutdown and that RF grounding to surrounding blanket modules should be implemented. A key design principle is the adoption of the highest feasible level of modularity throughout the design; this should simplify manufacture and reduce the spares requirement, and hence cost. The resultant design is shown in Figures 2, 3 and 4 and described in Sections 3 and 5.3.

5.2. Thermal and Disruption Loads

Peak RF currents of order 1-2kA will apply at several locations within the antenna, resulting in high thermal loads; a situation exacerbated by the power loading from radiation and neutrons emitted from the plasma. Resilience to disruption forces has required the design of RF windows that can transmit the forces on the central RF conductors to the port plug structure [10], which is based upon experience developed at JET in the use of double conical ceramic windows linked to titanium alloy inner and outer RF conductors (that allow a controlled use of the varying thermal expansion properties to pre-stress the ceramics [11]).

5.3. Design Status

The status of the design [12] for each major component is as follows:

Faraday screen: This forms the plasma facing component of the antenna, and consists of a series of the beryllium armoured bars comprising stainless steel tubing attached to a CuCrZr heat sink and a stainless steel backing strip shown in Figure 9. This provides an established manufacturing method (which still requires some R&D) and analysis has demonstrated its power handling capability to an average loading of $1MW/m^2$.

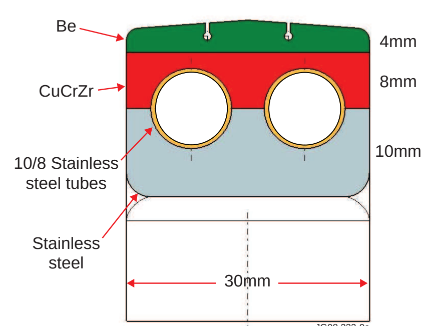

FIG. 9. Cross Section Through the Proposed Faraday Screen Bar.

Other Plasma Facing Components: Fault events can generate very high transient thermal pulses for plasma facing components. Consequently, many surfaces at the front of the antenna are clad in approximately 2mm of CuCrZr alloy, whose diffusivity limits the temperature rise to manageable levels. The use of copper alloy dramatically enhances disruption loads, and so assembly gaps between modules double as eddy current suppressing slots. R&D is being carried out to assess the use of honeycomb cores in the straps as a possible means of reducing disruption loads.

Shielding: There are two requirements for shielding: first that the maintenance γ dose rate in the port cell behind the antenna is below 100μSv/hr; and secondly that the window ceramic fluence does not exceed 10^{20}n/cm^2 within its four year lifetime. The present antenna design incorporates (a) stepping down the transmission line diameter from front to back to avoid a direct streaming path, and (b) a novel use of commercially available heat exchanger technology to obtain high water fractions in a matrix of micro channels. This has the potential to minimise pressure loads, enhance thermal performance, achieve a ~20% weight saving, ~5% improvement in shielding and suppress eddy currents. R&D is underway to optimise the channel geometry.

Core Conductor (shown in Figure 10): It is proposed to use the cylindrical RF surface of the core conductor as a pressure bearing shell. Internal coolant flow will be controlled by identical and interlocking guide disks. Velocity is higher in the periphery for enhanced cooling, and the core return flow is slow for minimised pressure drop. Keys enable a fixed angular progression between disks, conferring a swirl motion to the coolant flow, enhancing convection and shielding performance. Additionally, as the disks are neither structural nor in vacuum, boronated steel may be used to improve shielding performance. The laminate structure suppresses eddy currents, and so minimises disruption loads.

RF Vacuum Window (shown in Figure 11): The design concept [10] is that developed by Heikinheimo [11] using titanium alloy conductors and double conical ceramic insulators. The primary design feature is the use of pre-compression during cool-down from brazing by the mismatch in thermal expansion between the ceramic and titanium support structures.

RVTL: This has recently been upgraded, as shown in Figure 4, to include an in-vessel service stub. Neutron streaming was avoided and the RVTL envelope respected by packaging the stubs between toroidal TL pairs. The maximum length was limited by the insertion point and window access requirement, which excluded all conventional RF stub topologies, and consequently the design adopted a folded transmission line to obtain a compact geometry.

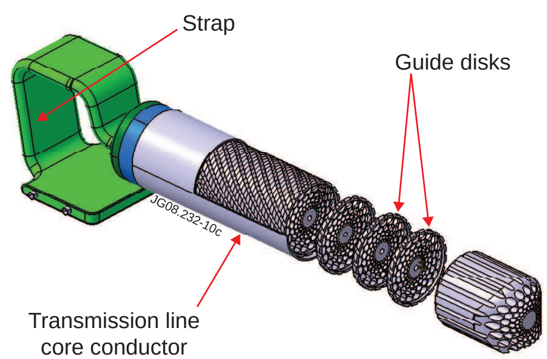

FIG. 10. Proposed Core Conductor.

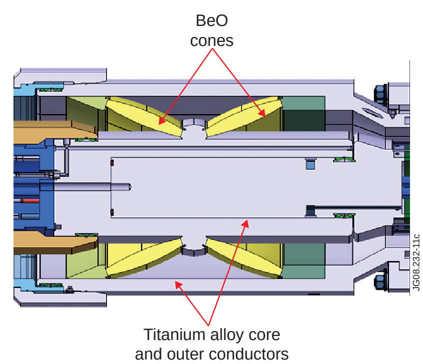

FIG. 11. RF Vacuum Window.

6. Conclusions and the EU Contribution to the ITER Antenna Design

A substantial amount of progress has been made in establishing a credible design for the ITER RF Antenna, but there are several key issues outstanding, and the design is likely to evolve further before a concept design can be approved. The near-term priorities for the work programme are to: clarify the RF engineering design features for the plasma facing antenna section; provide a concept-level cooling system design; and to confirm (with ITER and F4E) the mechanical engineering load specification and antenna functional specification. Over the last few years, antenna design has been carried out within the EU, with EFDA-funded support, by: CEA, ERM-KMS, UKAEA, IPP-Garching, and Politecnico Torino. This group are discussing the formation of a European consortium (CYCLE) that can bid for the forthcoming antenna design activities as part of the EU contributions to ITER coordinated by F4E. The EU team also plays a major role in the experimental development of ICRF systems, through facilities on JET, Tore Supra, ASDEX-U, and TEXTOR. These facilities can test: general RF coupling (all); conjugate-T operation (Tore Supra, JET, TEXTOR); ELM tolerance (JET, ASDEX-U); arc detection (all); sheath effects (Tore Supra, JET); and long pulse issues (Tore Supra). The EU team can support the design and experimental activities with (a) modelling capability, such as TOPICA, and (b) R&D in support of the EU ICRF programme (e.g. the recent construction of an RF mock up of the ITER antenna [5]).

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References

[1] BORA, D., et al., 17th Topical Conference on Radio Frequency Power in Plasmas, Clearwater, Florida, AIP Conference Proceedings 933 (2007) 25-32.
[2] SWAIN, D., and GOULDING, R., Fusion Engineering and Design, **82** (2007) 603-609.
[3] VULLIEZ, K., et al., Fusion Engineering and Design, **74** (2005) 267-271.
[4] NIGHTINGALE, M. P. S., et al., submitted to this conference (FT/4-5RA).
[5] DUMORTIER P., et al., submitted to this conference (IT/P7-8).
[6] DUMORTIER P., et al., submitted to SOFT 2008.
[7] LANCELLOTI V., et al., Nucl. Fusion **46** (2006) S476.
[8] MILANESIO, D., et al., Plasma Phys. Control Fusion **49** (2007) 405.
[9] COLAS L., et al., CEA Report PHY/NTT-2008.008.
[10] HAMLYN-HARRIS, C., et al., submitted to SOFT 2008.
[11] HEIKINHEIMO, L., et al., Fusion Engineering and Design, **55** (2001) 419-436.
[12] BORTHWICK, A., et al., submitted to SOFT 2008.