PROGRESS IN RF HEATING (IC, EC AND LH) DESIGN AND R&D DURING ITER EDA

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Abstract

The status of the design and of the technology development of the Radio-Frequency Heating and Current Drive (RF H&CD) systems performed during the ITER EDA is summarized.
The conceptual designs of three RF systems [Electron Cyclotron (EC), Ion Cyclotron (IC) and Lower Hybrid (LH)] are now completed. In view of ITER severe in-vessel operating conditions, the maximum emphasis was given to the design of the in-vessel components. In the R&D program, technology progress has been achieved in several critical areas of all three systems, both in base technology (such as in gyrotron and windows developments for EC) as well as in design validation (IC prototype antenna, LH transmission components).

1. INTRODUCTION

The analysis of ITER physics scenarios suggests that a minimum auxiliary heating and current drive power of 100 MW (with a desirable extension capability to 150 MW) can cover all ITER operational needs.

H&CD requirements vary during the different phases of the discharge and possibly change during the ITER lifetime, depending on the evolution of the physics program. They range from bulk central heating, in the H-mode access and pre-ignition phase, where direct ion heating, provided by the IC system is an advantage, to localized electron heating (typical of EC) for plasma kinetic control, stabilization of MHD modes and sawtooth suppression during burn, and to off-axis current drive (for which LH provides the best performance) for shear and profile control and discharge optimization. Auxiliary, but important, functions, also assigned to the heating system are plasma start up and wall conditioning, the latter possibly continuously required during the interpulse period.

A substantial versatility is thus required for the ITER H&CD systems. As at present no single system appears to be capable of efficiently carrying out all duties, more than one heating systems is planned to be in operation at the same time. To cover these diverse requirements, three H&CD systems (Electron Cyclotron, Ion Cyclotron and Lower Hybrid) and a (negative ion) Neutral Beam Injection system have been designed and developed during the ITER EDA. The RF systems are reviewed in this paper.

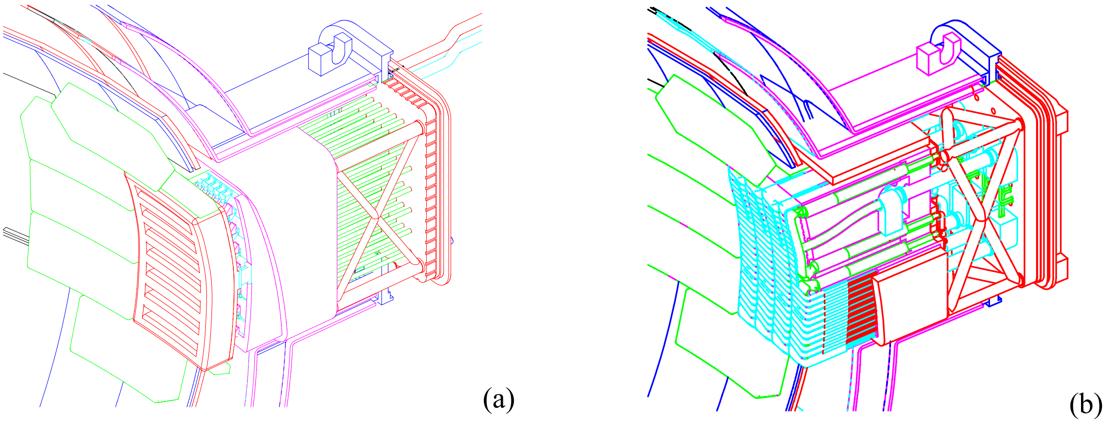

FIG 1. a) Integrated Electron Cyclotron and b) Ion Cyclotron plug-ins.

To allow these systems to be flexibly used, and to facilitate interchangeability, a modular approach has been adopted in the design of the RF systems (see examples in Figure 1). All systems are designed for a power output of 50 MW CW and are integrated in ITER equatorial ports. They provide adequate neutron shielding, are easily removable through the port with similar manual and Remote

Handling (RH) operations, and do not modify the torus layout or extend its vacuum and tritium boundaries. From a construction point of view, the RF plugs share a common support structure design, port closure plate, vacuum feed-through position, and RH tooling.

2. EC SYSTEM DEVELOPMENT

The EC System is designed to launch elliptically polarized, ordinary-mode EC waves from the low-field side of the machine. The selected frequency of 170 GHz provides the necessary capabilities for heating and current drive. A separate system operated at 90 and 130 GHz is designed for start-up and wall conditioning functions.

The injection system features an innovative design, with each of the 56 array wave guides injecting through a pair of mirrors, one of which is toroidally steerable by 30˚. Work has focused on identifying the critical design issues of both in-vessel transmission and injection system. Detailed designs of the mirror, cooling connections, and actuation mechanisms, have been developed. Prototypes have been constructed and tested.

The mirror, is mounted on a flexible pivot (Figure 2a), which provides rotation about a vertical axis of ±15˚. Interwoven helices provide inlet and outlet paths for the cooling water. The mirror assembly is thus free of bearings and bellows. A prototype mirror has been fabricated and tested with a heat source providing about 2 MW/m^2 peak, closely simulating the RF beam profile (Figure 2b). IR temperature measurements of the surface confirm that the heat transfer and temperature rise are consistent with design specifications.

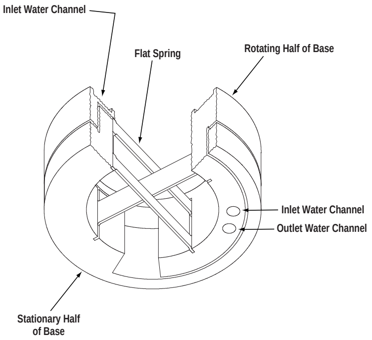

FIG. 2a. Steering mirror rotating pivot

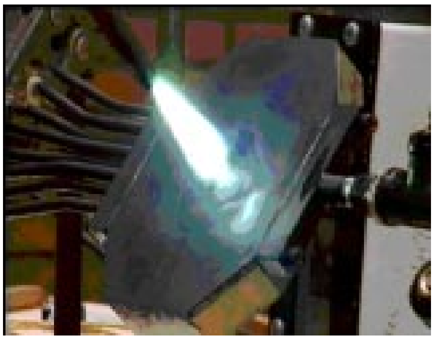

FIG 2b. Thermal load test on EC mirror.[1]

In view of the difficulty of designing a highly reliable mechanical component for use near the plasma, alternative methods are also being examined. A promising approach is called "remote steering." Using this method, the mechanical components can be moved either to the outside of the vacuum vessel or located within the vacuum vessel in a well shielded area unexposed to the plasma fluxes and disruption forces. Details of the method and results of experimental measurements are presented in the companion poster.

Electron cyclotron H&CD relies heavily on the development of gyrotron and window technology [2]. The two items have been the primary focus of the ITER EDA R&D program, the main goal being the demonstration of a 170 GHz, CW, ~50% efficient, 1 MW gyrotron, together with dielectric windows for use on the torus and tube. Within the final four years of the EDA, the best gyrotron power performance at 170 GHz is 1 MW output for up to 2 s and 1.75 MJ in 10 s operation. Demonstration of a high efficiency (~50 %) depressed collector operation at 100, 140, and 170 GHz was also obtained.

One of the major successes of the development program has been the demonstration of a water cooled, single disk, diamond window. The technology to manufacture large diameter diamond disks has been developed and the material quality rapidly improved. The technique to bond the disks to metal tubes has been demonstrated, prototype bonded disks have established their feasibility for use on gyrotrons, high power tests of the material at 170 GHz have been made, and a complete window assembly has been fabricated and operated on a tube.

3. IC SYSTEM DEVELOPMENT

ITER IC system design is based on an antenna scheme well tested in present tokamak operation: the Resonant Double Loop (RDL). An IC array consists of a matrix of 4x2 RDLs. The adopted frequency range (40 to 70 MHz) encompasses the principal IC heating scheme at the $2\Omega_T = \Omega_{He3}$ resonance, (57 MHz at full B_T,), successfully demonstrated in D-T plasmas in TFTR and JET, with Ω_D (42 MHz at full B_T) as an alternative. Fast Wave Current Drive (FWCD) is in the frequency window between $2\Omega_T$ and Ω_{He4}, (62.5 MHz), where electron absorption is high. The system uses four equatorial ports to deliver 50 MW, at a nominal plasma/separatrix distance of 15 cm. If the plasma wall distance were reduced to 10 cm, two ports could be sufficient to couple 50 MW.

The current strap is fed by one coaxial transmission line (supported by all-metal supports [3]) about the centre of the strap, and tuned at the two ends by two variable reactances (pre tuners). A resonant $\lambda/2$ double loop results, whose electrical length can be adjusted by the pre-tuners to different frequencies and plasma loads. The (resistive) input impedance is matched to the nominal characteristic impedance.

Extensive characterizations of the prototype antenna have been performed with and without a Faraday shield and the experimental results have been analyzed with the help of ARGUS 3D EM code (Figures 3 a and b).

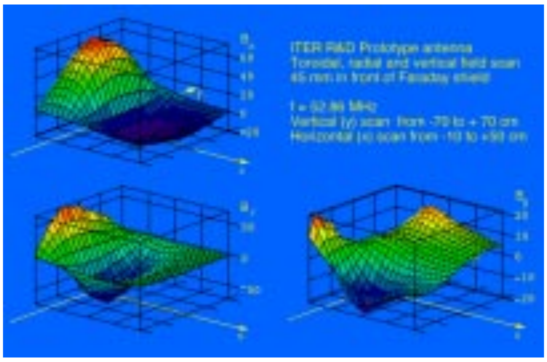

FIG. 3a. Prototype antenna characterization: 3D B-field components of the RF emission

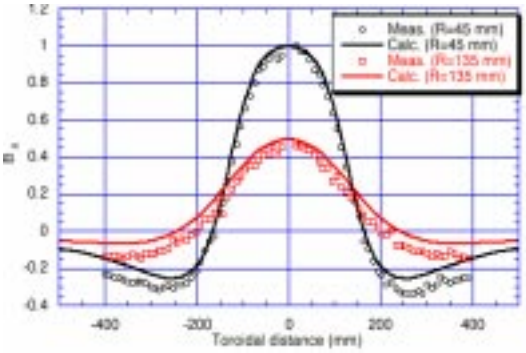

FIG. 3b. Example of comparison between computed and measured date

The agreement is generally good (Figure 3b), providing an essential background for an accurate prediction of plasma coupling.

One of the important parameters affecting the reliability of operation is the maximum operating voltage, which is dependent on plasma coupling. Present estimates show that, due to the low plasma coupling in ITER (R_c ~3 Ω/m), the maximum system voltage exceeds 50 kV. Therefore, specific antenna optimization studies for high voltage operation have been carried out in the R&D program [4] and validation tests have been performed in vacuum on a full scale prototype. The prototype tests have demonstrated that RF voltages over 60 kV can be maintained for time intervals limited by overheating only. Figure 4 shows a pulse of two seconds at an antenna voltage in excess of 60 kV.

4. LH SYSTEM DEVELOPMENT

The LH System has been designed by the EU Home Team to provide extension of ITER pulse duration, sawteeth control, off-axis current profile control during burn, and non-inductive current drive in advanced tokamak scenarios. The launcher and transmission line design features important innovations with respect to today's systems, and feasibility tests on existing tokamaks are planned, in order to validate the adopted solutions. The system operates at 5 GHz and uses two ITER ports. The launcher design is based on the concept of the passive active multijunction (PAM). Four PAMs are used for each antenna. Each PAM is connected to an hyperguide fed by 24 TE_{10-30} mode converters. The operating power density is about 23 MW/m^2 (waveguide cross section), now routinely achieved in present experiments at 3.7 GHz. Calculations show that the PAM assembly is an

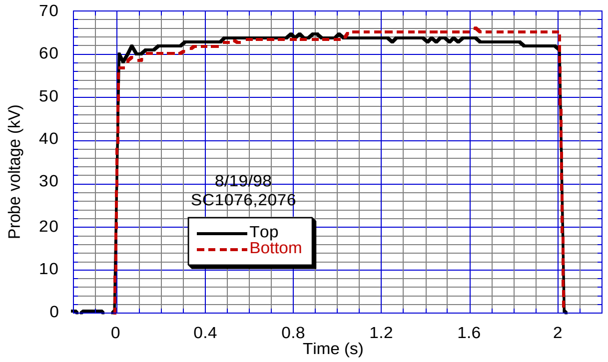

FIG. 4. High voltage test on IC antenna prototype

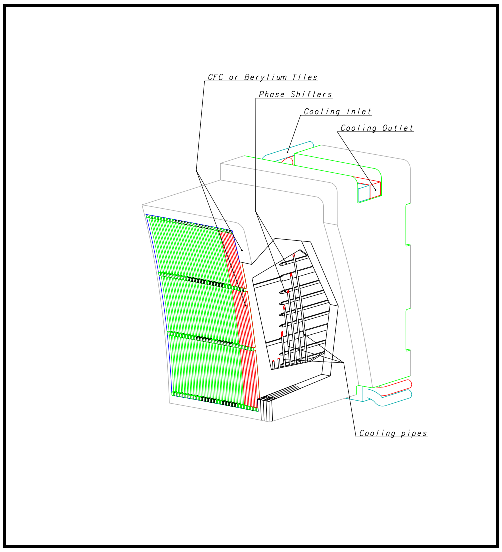

FIG. 5 Lower Hybrid PAM stack

efficient neutron and radiation shield. The launched $N_{//}$ spectrum, produced by a PAM stack of 29 passive and 28 active waveguides, (Figure 5), with a 270° phasing, is fixed at $N_{//}=2$. Each antenna is fed by 8 main transmission lines, each consisting of a splitting network connected to 6 RF windows, one oversized size (C10) circular transmission line, operating in the TE_{10} mode, and a recombining network, to combine the power of 4 klystrons. The LH H&CD plant is composed of 64 klystrons of 1 MW in CW operation.

Specific components, such as the mode converter and the hyperguide have now been successfully tested at high power and long pulse duration. However, an intensive design R&D validation program is planned to test a full scale module of the LH antenna. The program will focus on the validation of the PAM concept together with a splitting network made of hyperguides and mode converters.

The launcher design [5] has been adapted to 3.7 GHz to be tested on Tore Supra, as it has a unique capability for long pulse and high heat load operations. The ITER-like launcher is made of 2 PAM modules of 17 passive waveguides. Each PAM is fed by a TE_{30} hyperguide fed by 4 TE_{10-30} mode converters. The power density in the wave guide is below 38 MW/m^2 for a maximum injected power of 3.5 MW. The main $N_{//}$ peak is at 2 for a directivity of 67%. The transmission line recombines the power from 8 existing 500 kW klystrons into a circular C14 transmission line. The recombining and splitting network, as most ex-vessel components are similar to the ITER design and based on technologically mature components.

5. CONCLUSIONS

The RF systems design developed during the ITER EDA appears to be adequate to provide the H&CD functions required in all ITER scenarios and to offer the prospect of reliable operation. Substantial advances in technology have taken place in the parallel R&D programmes. Design validation has taken place wherever necessary and possible. The modular approach to the design is likely to provide a sufficient degree of flexibility to accommodate future physics needs as well as future technological progress.

6. REFERENCES

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