Interface Issues associated with the ITER ECH system

M.A. Henderson[1], G. Saibene[2], T. Bonicelli[2], R. Chavan[1], D. Farina[3], D. Fasel[1], R. Heidinger[4], E. Poli[5], G. Ramponi[3], O. Sauter[1], H. Zohm[5]

[1] CRPP, EURATOM – Confédération Suisse, EPFL, CH-1015 Lausanne Switzerland
[2] EFDA Close Support Unit, Boltzmannstrasse 2, D-85748 Garching, Germany
[3] Istituto di Fisica del Plasma, EURATOM- ENEA- CNR, 20125 Milano, Italy
[4] Forschungszentrum Karlsruhe, EURATOM-FZK, D-76021 Karlsruhe, Germany
[5] IPP-Garching, Max Planck-Institute für Plasmaphysik, D-85748 Garching, Germany

First Author e-mail: mark.henderson@epfl.ch

Abstract
The ITER ECH system, is an in kind procurement consisting of power supplies, gyrotrons, transmission lines and launchers supplied by five parties (EU, IN, JA, RF and US). Each of these subsystems have to interface not only between themselves but also with the ITER auxiliary and control systems. The management of interfaces is therefore essential for the system to guarantee the required performance, availability and reliability. The objective of this paper is to review the present ITER ECH system looking at the status of each subsystem. Then review the integration of these subsystems as a single unit into the ITER structure. Weak links of the EC susbsystem will be identified and when possible alternative solutions will be suggested.

Introduction
Two operating frequencies are being planned for the ITER ECH system 127.5GHz and 170GHz. The lower frequency is to be used for startup (SU) assist and will be generated from three 1MW sources operating for ≥10s. The higher frequency will be used for heating and current drive (H&CD) applications and generated from up to 24 continuous wave (CW) gyrotrons operating between 1 and 2MW. The main EC subsystems include the power supplies, gyrotrons (and associated auxiliary systems), transmission lines and two types of launchers (equatorial and upper) as illustrated in figure 1.

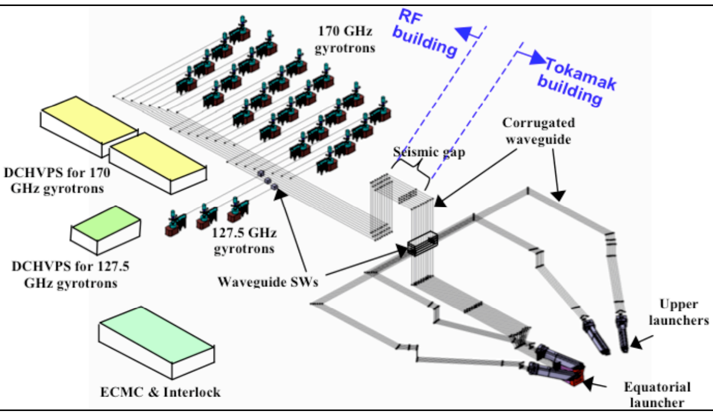

FIGURE 1. Overall ITER EC system (as described in Ref. [1]) comprised of power supplies, two gyrotron types, transmission lines and two launcher types.

The technical specifications and/or build-to-print design of each subsystem is provided by the ITER International Team (ITER-IT), details of which can be found in the relevant ITER documentation. Each of the participating parties then provide the various subsystems as in-kind procurements as outlined in figure 2. These subsystems are then delivered to ITER-IT, which then integrate the whole system together in time for the first plasma presently scheduled for March 31, 2016. ITER-IT and the associated parties involved in the procurement faces several challenges in preparation for the ‘day 1’ operation of ITER, for simplicity these challenges are grouped into three categories: subsystems status, baseline design, and interface management. The aim of this paper is to review briefly each of these challenges.

Subsystem Design & Manufacturing Status

Starting from the power supplies and reviewing each subsystem up to the launcher, one realizes that the status of each component is progressing at a rate consistent with requirements for first plasma on March 31st, 2016. There are two possibilities for the power supplies [2]: thyristor or pulse step modulated (PSM) both of which are roughly comparable in costs. The PSM based system would have a single power supply per two gyrotrons providing a greater flexibility in gyrotron operation and is commercially available. The thyristor based design would have two supplies each powering 12 H&CD gyrotrons with a high voltage solid state switch (HVSSS) used to turn on/off or modulated groups of two gyrotrons. Aside from additional R&D needed for improving the modulation frequency of the HVSSS from 1 to 5kHz, either power supply configuration could be used for ITER.

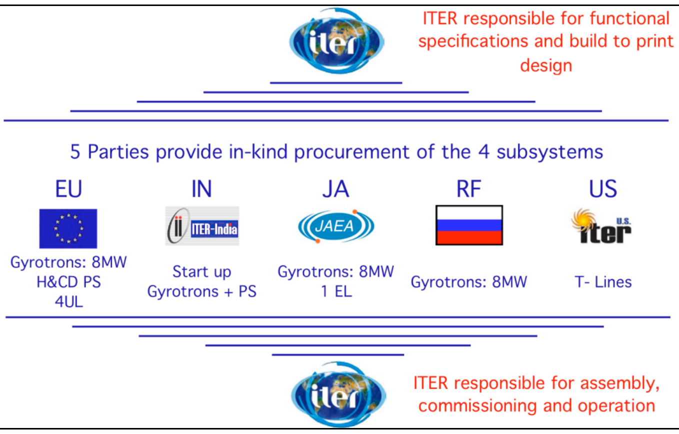

FIGURE 2 The roles of the five parties and ITER in providing four subsystems forming the EC system.

The most critical subsystem is probably the gyrotrons, which are to provide ≥1MW RF power and must operate with a very high reliability to insure that the 3MW for SU and 24MW of H&CD are available for operation. Progress for the H&CD gyrotrons has been progressing rapidly in the past 15 years from 0.5MW 2s operation to the most recent advancement of 1MW ≥800s operation of the ITER compatible gyrotron demonstrated by JAEA [3] and followed closely behind by GYCOM with 0.95MW and ≥100s [4]. The next 8 years provides adequate time for optimizing the gyrotron designs for improved efficiencies and even operation to higher power as planned for the 2MW coaxial gyrotron planned for the European contribution [5].

The output power from the gyrotron will be transmitted to the launchers via evacuated 63.5mm diameter corrugated HE_{11} waveguide, which provides high transmission efficiencies in a very compact volume. JAEA has demonstrated the efficient transmission of the RF power at 1MW ≥800s pulses lengths in a relatively short transmission line length associated with the JAEA gyrotron test stand [6]. Several of the components comprising this transmission line were purchased from General Atomics, Inc., which can provide ITER compatible components, a majority of which compatible with 2MW CW transmission [7]. Components (such mitre bend polarisers and in-line switches) not compatible with 2MW CW operation are being modified or alternative components are available to achieve equivalent performance.

The launchers are the last component prior to the plasma. There are two launchers planned for the ITER EC system: the equatorial (EL) and upper (UL) port launchers [8,9]. A front steering mirror is used to sweep a set of beams in either the toroidal plane (EL) for maximizing the driven current or vertical plane (UL) for optimizing the peak current density. An optimized partitioning of the physics applications has been proposed that uses the strengths of each launcher for an enhanced performance of the EC system, while relaxing many of the engineering constraints [10]. The critical issues of both launchers have been resolved on a detailed design level and test programmes are under way for demonstration of reliable operation in the ITER environment.

In summary, the status of the main subsystems is very positive with no critical issue left unresolved.

Base-Line design Status

As stated above, ITER-IT is responsible for the technical specifications of all subsystems and in some cases (such as the launchers) even the build-to-print design. In reality, ITER-IT was not established with the necessary resources to perform these responsibilities and therefore it is the parties that have contributed to specifying the functionality and designing the various subcomponents of the ECH system. The parties had to take this initiative in order to provide the subsystems on time, but the situation introduces potential complications with the integration of the subsystems. This is best exemplified by the H&CD gyrotrons, where three significantly different gyrotrons (1MW diode with cylindrical cavity, 1MW triode with cylindrical cavity and 2MW coaxial cavity) are being developed by the various contributing associations. The design variation can be attributed to the ambiguity in the various reference documents that outline the technical specifications: Procurement Package (PP) [11], Project Integration Document (PID) [12] and the Design Description Document (DDD) [13]. Unfortunately, there is no single reference that can be used in guiding the different parties in designing a given subsystems. The three reference documents have conflicting information, which can lead to significant conflicts when assembling and operating the EC system. This is exemplified in Table 1 where examples are given for the gyrotrons, in-line switch and upper launchers.

The PP has three different suppliers providing the H&CD gyrotrons, and all are different and can not simply be interchangeable as required by the DDD. Part of the complications are due to the fact that two of the base line documents were written based on older technologies prior to the installation and operation of the multi-megawatt systems in operation today. For example the older documents (PP and DDD) specify the use of k-spectrometers and manual switches, while the PID has been recently revised with some removed or replaced based on modern technologies like fast remote controllable switches. The PID has also been upgraded to account for recent advances in the physics achievements obtained from existing machines. For example the UL has been shown to be more effective for sawtooth control [10,15] than the EL, shifting the sawtooth application to the UL requires the use of four ports, while the PP and DDD are still based on a three ports for the UL.

Having the two thirds of the baseline documents essentially based on mid 1990 technology on a fusion device planned for 2016 limits not only the technological functionality but also the ultimate physics performance and operational reliability. A revision of these documents is necessary to take advantage of the experience gained in existing multi-megawatt EC systems on present tokamaks and stellarators.

TABLE 1 Examples of inconsistencies between the three base-line documents defining the ITER EC system.			
	Procurement Package	Project Int. Doc.	Design Descrip. Doc.
Date	2000	2007	2001
H&CD Gyrotrons	3 suppliers		Interchangeable
Switches	manual	remote	manual
# of UL/ beams per port	3 8	4 6 or 8	3 8

Interface Management Status

The status of each subsystem provides the EC community with a sense of optimism, since the majority of all critical design issues have been resolved. However, a high operating reliability does not depend solely on assembling perfect subcomponents, but also on how the subsystems are assembled to form a single operating system. The system reliability depends on its weakest link, which could either be a component or an interface between two subsystems. Each subsystem has to be designed with respect to its neighboring component to insure an optimum match. Four simple examples of interface issues are listed below:

1. The output mode from the gyrotron has to have a high Gaussian content and of the correct beam waist, location and injection angle to insure a high percentage of the power is coupled to the HE_{11} mode propagating in the corrugated waveguide. Otherwise, high losses will occur in the waveguide risking high power densities.
2. The layout of the waveguide and gyrotrons have to designed to insure optimum access around the gyrotrons for installation and maintenance. The layout should be as modular as possible to insure all maintenance tasks are simplified.
3. The launchers installed in the upper port may move up to ~50mm in the radial and vertical directions during thermal and operating cycles. The transmission lines connected to the launcher have to be designed to accommodate such movements, otherwise the waveguides will bend and could experience plastic deformation.
4. The transmission lines near the launchers should be routed to provide optimum access to the launcher for maintenance. A minimum of components should be removed in the event of launcher removal.

These issues and numerous others are often relatively straight forward, but require each subsystem to be designed with a view of the entire ECH system. The interface management required for the integration of the ITER EC system is complicated by the in-kind procurement plan, with the various designers distributed throughout the international community rather than at one location on the ITER site.

Interface management for the ITER EC system is also complicated due to the severe limited resources ITER has to manage the integration of the entire EC system. This is highlighted when considering the human resources required to design and integrate the various subsystems of the existing EC systems on the various devices in operation around the world. A design team spanning several expertise is required for integrating the power supplies, gyrotrons, transmission lines, launchers and associated cooling, vacuum, control and mechanical systems, typically requiring ~5 person years per year (py/y) as illustrated in table 1. However, the ITER-IT has only a single individual dedicated to the EC system and working 0.5py/y. In addition, the ITER EC system is more complicated than the existing systems with a greater number of gyrotrons, a more complicated control system and requires compatibility with nuclear issues such as tritium containment, exposure rates, limited material choices with in-vessel components and compatibility with remote handling requirements.

Table 1 Approximate human resources required for integrating the EC subsystems on various existing tokamaks and stellarators as compared to ITER.				
Device	# of Gyrotrons	P_{RF} available	D-T	Design Team
TCV	9	4.2MW	no	~5py/y
DIII-D	6	4.1MW	no	~5py/y
LHD	9		no	~???py/y
ASDEX-Upgrade	5	2.5MW	no	~5py/y
FTU	6		no	~???py/y
JT-60U	4	2.8MW	no	~4py/y
ITER	24	20MW	yes	0.5py/y

Managing the interfaces has to occur early in the design stage, so that each subsystem can be designed to be integrated into the EC system. Otherwise, the subsystems will require modification during either the manufacturing or installation phase. Either of which will result in cost over-runs and delays. For this installation and assembly process to proceed smoothly, the fitting of the pieces together has to be insured now not upon delivery of the subcomponents. Note that the entire EC system is to be installed during only a ~2 year period from early 2014 to late 2015 in preparation for the first plasma operation scheduled for March 31st, 2016.

Conclusion

The EC community has made considerable technological advances associated with the principle subsystems (gyrotrons, transmission lines and launchers) of the EC system. However, there is a lack of resources being devoted to the integration of these subsystems to form a cohesive ECH system for ITER. These resources are not available in the limited ITER-IT. The situation is complicated with a lack of a single reference design document. To alleviate these shortcomings, the EC community has to work together to provide a complete EC system consistent with the ITER requirements and mutually compatible with all the associated subsystems.

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