Implications of ITER requirements on R&D of RF Heating and Current Drive Systems

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Abstract. Heating and Current Drive (H&CD) systems have an essential role in ITER-FEAT operation, as all phases of ITER operation are driven and controlled by the auxiliary power flow. The RF (Electron Cyclotron and Ion Cyclotron) systems, planned to contribute for ~ 60% of the total auxiliary power (72 MW), with Lower Hybrid used for the specialised function of current drive in the extended performance phase (20 MW), are at different level of technology development. All systems, need a significant development in order to meet ITER operation requirements In this paper these requirements are reviewed and CEA proposals for the development of the Ion cyclotron system presented.

1. Introduction

Heating and current drive (H&CD) systems play an essential, rather than auxiliary, role in ITER, as all phases of the operation – break down and assisted current rise, access to the H-mode regime, achievement of a driven burn, control of the excursions about the operating point, suppression of MHD, pressure-driven and NTM instabilities, current drive and current profile control, up to the achievement of a soft pulse termination – are driven and controlled by the output power of H&CD systems.

H&CD by Radio-frequency waves contributes for about 60% of ITER auxiliary power (72 MW). Three RF heating candidate methods have been retained during ITER-EDA. Electron Cyclotron (EC), Ion Cyclotron (IC) and Lower Hybrid (LH) systems have been designed. R&D requirements have been identified for all systems, and resources for development allocated as reported in Table 1.

TABLE 1: R&D RESOURCES ALLOCATED DURING ITER-EDA [1]

	Total (M$)	EU (M$)
Electron Cyclotron	24.8	5.6
Ion Cyclotron	7.25	3.9
Lower Hybrid	0.15	0.15

ITER performance will be more critically depending than in current fusion devices on the level of *efficiency*, *reliability*, and *versatility* of its H&CD systems.

To reach a suitable level in these three essential requirements, a significant progress in the technology of essential components is still needed for some system, and, for all systems,

- an upgrade to ITER requirements of most power generation and transmission equipment must be performed;
- a convincing demonstrations of operating capability in ITER relevant conditions must be provided;
- an efficient integration of these complex and multi-technology systems in ITER operation must be achieved.

2. Technology requirements and issues

The capability of *quasi-continuous operation* is outstanding among the technology issues to be urgently tackled and resolved, as suitable equipment at the desired power level and operational experience is not available. RF power generation and transmission systems used in fusion H&CD experiments operate for pulse length of tens of second and are not designed, nor optimized, for quasi-continuous service. For some equipment, the upgrade to CW operation is rather straightforward, but for other, a substantial re-design is required.

Particularly urgent is the development of suitable power sources. In Table 2 a summary of required and actual performances of RF power sources are reported for the three methods. A period of four years and a substantial investment is likely to be needed to achieve the required performances and a similar period may be required for the production.

TABLE 2: REQUIRED AND CURRENTLY AVAILABLE PERFORMANCES OF ITER RF POWER SOURCES

System	EC		IC		LH	
	Required	Achieved	Required	Achieved	Required	Achieved
Output power (MW/tube)	1.0	0.9 0.2	2.0/2.5	1.5	1	0.5
SWR	1.1	1.1	2.0/1.5	1.1	1.1	1.1
Frequency (MHz)	170,000	170,000	30-55	30-55	5,000	3,700
Pulse length (s)	1000	10 133	1000	1000	1000	1000
Efficiency (%)	50	45	65	65	60	45

From an operational point of view, an efficient long pulse operation calls for a significant upgrade of real-time *equipment diagnosis, control and protection*. Due to the high RF power density required in ITER operation, the long pulse capability of the heating systems may become a potential problem. Power faults, causing uncontrolled power deposition in the torus or in some part of the heating system, must be very rapidly identified, in order to prevent severe damage.

The large quantity of data, potentially collected in a single long pulse imposes *new real time data reduction and analysis*, and *new man/machine interface methods* for an efficient data inspection. In *protection systems*, reliability is often in conflict with power transfer efficiency, since protective actions often temporarily suppress or reduce the power flow, and over-concerned protection monitors can cause a significant inefficiency. P*ower redundancy* should be available on-line, to maintain the required power flow during power trips, and protection systems should be capable of recovery to operation, in a safe and ordered manner.

A *higher level of sophistication and autonomy* is requested for ITER subsystems control. A close integration between the H&CD supervision system(s) and machine control is necessary to implement physics scenarios of increasing sophistication, adopted to extend the boundaries of the physics operation.

A general *increase in the efficiency of power generation/transmission systems* is desirable for all RF systems, in order to reduce massive cooling requirements and unacceptable overall power balance. At present, 50 % efficiency is optimistically considered a target for next step RF systems, but this figure is likely to be insufficient for a driven demonstration reactor.

Finally, a substantial *improvement of the general H&CD systems availability* is necessary to minimize ITER operation time and cost.

It is well known that the *overall availability of the current auxiliary systems needs to be improved* and *some streamlining in selecting the duties of the H&CD systems may be of help*. During EDA, all H&CD system have been developed for the widest possible range of service, in some case at the expense of a significant increase in the complexity of the design. There is a significant overlapping in the projected capabilities of different systems and some effort avoiding features needed only for secondary purposes, may help improving reliability.

For example, simpler and more reliable IC and EC launchers could be conceived if respectively specialized in their primary functions of on-axis plasma heating and off-axis NTM mode stabilization, both essential for the initial ITER high β inductive scenarios. For the latter system, the use of the much more advanced 140 GHz gyrotrons could also be possible. .

Once developed, *efficiency and reliability of the H&CD systems should be demonstrated* on existing machines, or on purpose-built test stands, before application to ITER. If not, the process of improvement to full performance of the heating systems, during the initial ITER operation, would be too long and expensive, as it has been the case for many current experiments. The use of existing high performance devices as plasma test stands, obviously more desirable, because including “in vivo” operational features, could be possibly faster and cost effective, if properly organized.

3. Implications of ITER requirements on R&D

During ITER-EDA, a total of 32.2 M$ was allocated to R&D on RF H&CD systems. Most (~ 80%) resources were devoted to the development of a 1 MW, 170 GHz, continuous wave gyrotron source and associated vacuum window. Only ~ 50 % of the resources allocated to IC were actually spent, and devoted to the development of mock-ups to validate aspects of the IC launcher design. R&D resources for the Lower Hybrid system were postponed to the construction phase, as the LH system operation is planned for the ITER extended performance phase.

As from day one ITER operation fully depends on auxiliary heating, the goal of the future R&D on ITER H&CD is to provide three efficient and reliable systems in about 10 years.

In the ITER procurement scheme, RF power sources and transmission systems are regarded as existing commercial items, for which no specific R&D should be needed. From the inspection of Table 2 it is quite clear that a substantial R&D investment must be devoted early in the ITER construction period, in order to complete the basic development of the EC power sources and to upgrade to quasi-continuous operation IC and LH sources.

One should also bear in mind that the production phase of the ITER sources is relatively long (~ 4 years are planned in ITER procurement packages), because of the need of upgraded factory test stands and for relatively long post-production test procedures. A vigorous pre-industrial upgrade for the IC and LH sources should be started now, to make CW tubes available for power tests on test stands and existing machines.

A parallel R&D development should be dedicated to transmission equipment, also in view of the fact that the operating frequencies proposed for ITER for EC and LH (170 and 5 GHz) have never been used in previous experiments.

Design but little R&D has been so far carried out on ITER RF launchers. In the ITER procurement, manufacturing of the launchers of all three RF systems is considered as “build to print”, i.e. carried out “according to a fully specified design, provided to produce fabrication/shop drawings, and with no R&D development required to the manufacturer”.

Fully commissioned launcher prototypes must be developed before the ITER procurement starts. If one takes as typical the time scale the JET-EP ITER-like Ion Cyclotron antenna (~ 1/2 of ITER installed power, with no provision for CW operation, nuclear shielding and cooling) for the development of an ITER RF launcher prototype, this would require in excess of four years.

Based on the above considerations, a generic 10-years development plan for the RF H&CD systems would be the one in Table 3. To fit in the plan, the R&D on gyrotrons should be completed in two years. The upgrade of existing IC power sources to ITER requirements should be started to make the power sources needed for a launcher prototype available.

A parallel development of a ITER prototype EC and IC launcher prototype (and as some later date on the transmission system) should be take place in parallel and completed in 3-4 years. Testing the prototype should not exceed ~ 2 years. The subsequent procurement and installation for the first batch of (20+20 MW) of ITER RF heating would last about five years

The LH system is required in ITER for the extended performance phase, or 5 to 8 years after day one. However a longer development should be planned since a never tested launching scheme (the PAM (Passive/Active Multi-junction) scheme) and a frequency for which the power source is not yet available (5 GHz) are proposed. The ITER prototype must be therefore developed and tested at 3.7 GHz, where equipment and sources exist.

TABLE 3.: GENERIC 10-YEARS DEVELOPMENT PLAN FOR THE RF H&CD SYSTEMs

YEAR		1	2	3	4	5	6	7	8	9	10
	Launcher	Proto Development			Test on plasma		Procurement				Install
IC	T.Line					Devel.	Components production			Installation	
	RF Source	Proto development				Test on plasma		Procurement			Install
	Launcher		Proto PAM @5 GHz			Test on plasma		Procurement ⇒			
LH	T. Line				Development		Components production			Installation	
	RF Source	Proto development @1MW , 5GHz				Test on plasma		Procurement ⇒			
	Launcher	Proto development			Test on plasma		Procurement			Installation	
EC	T.Line				Development		Procurement			Installation	
	RF Source	Proto Develop.		Production	Test on plasma		Procurement				Install

Based on the above generic time scale, CEA has recently proposed a 10-years plan for the development of the ITER Ion Cyclotron system The main features of the development, are outlined in Table 4.

TABLE 4: MAIN FEATURES OF CEA PROPOSAL FOR THE ITER IC DEVELOPMENT

Technical achievement	Development and demonstration of an ITER ¼ size prototype: Component Launcher, transmission, power source: 4MW,CW, 35-60 MHz
Component to be developed	Antenna structure according to ITER design, In vessel tuning, actuation, monitoring and protectionsVacuum feed through
Components to be procured	Transmission system, power sources, including monitoring and control system
Prototype validation **Functional** **Full performance**	 Low power test bed, High power test stand TS runs Proto 2003 (2004),JET EP (2005) , TS Proto (2006)

4. Conclusions

Significant changes in the requirements, in the design, in the testing procedures, and in the operation of RF systems are necessary for ITER operation.

The equipment reliability and availability must be improved, and validated in realistic conditions, before their application to ITER.

In consideration of the ITER projected construction time, this process should start right now, with coordinated programs, clear targets and defined time scales, avoiding duplication of efforts.

Reference

[1] Fusion Engineering and Design **55**/2-3 87-358, (2001).