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Status of Europe's contribution to the ITER EC system

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Abstract. The electron cyclotron (EC) system of ITER for the initial configuration is designed to provide 20MW of RF power into the plasma during 3600s and a duty cycle of up to 25% for heating and (co and counter) non-inductive current drive, also used to control the MHD plasma instabilities. The EC system is being procured by 5 domestic agencies plus the ITER Organization (IO). F4E has the largest fraction of the EC procurements, which includes 8 high voltage power supplies (HVPS), 6 gyrotrons, the ex-vessel waveguides (includes isolation valves and diamond windows) for all launchers, 4 upper launchers and the main control system. F4E is working with IO to improve the overall design of the EC system by integrating consolidated technological advances, simplifying the interfaces, and doing global engineering analysis and assessments of EC heating and current drive physics and technology capabilities. Examples are the optimization of the HVPS and gyrotron requirements and performance relative to power modulation for MHD control, common qualification programs for diamond window procurements, assessment of the EC grounding system, and the optimization of the launcher steering angles for improved EC access. Here we provide an update on the status of Europe's contribution to the ITER EC system, and a summary of the global activities underway by F4E in collaboration with IO for the optimization of the subsystems.

1 Introduction

The EC system of ITER for the initial configuration will provide 20MW of RF power into the plasma during 3600s and a duty cycle of up to 25% for heating and (co and counter) non-inductive current drive, also used to control the MHD plasma instabilities. The system is comprised of 12 high voltage power supplies (HVPSs), 24 gyrotrons at 170GHz, 24 transmission lines (TL), 1 equatorial launcher (EL), 4 upper launchers (UL) and an integrated plant level control system (ECPC). This system is being procured by 5 domestic agencies, Europe (F4E), Japan (JA-DA), India (ITER-India), Russia (RF-DA), United States (USIPO), plus the ITER Organization (IO). F4E has the largest fraction of the EC procurements, which includes 8 HVPSs, 6 gyrotrons, the ex-vessel waveguides (includes isolation valves and diamond windows) for all launchers, 4 ULs and the ECPC. The large contribution covers nearly the entire spectrum of the EC system from plug to plasma.

F4E is also working with IO to improve the overall design of the EC system. Several task agreements have been signed for the design of components and subsystems, analysis of the critical interfaces, and engineering analysis and assessments of the EC heating and current drive (H&CD) physics and technology capabilities. This collaborative approach is promoted for the preparation of the specifications of the F4E R&D and

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supply contracts, seeking optimisations and simplifications reducing technical risks and containing cost. In addition, the strong involvement of IO during the technical monitoring of these contracts is crucial to ensure a smooth integration of the EC subsystems in ITER.

In this paper the present status of the EC subsystems under the EU responsibility is provided in Section 2, and examples of the optimisation process are presented in Section 3.

2 Status of the sub-systems under the EU contribution

2.1 HV Power Supplies

A number of changes have been made in the recent years to the functional configuration of the ITER EC HVPS, which was originally based on two thyristor-based PS, to accommodate for the (at least) 3 potential different gyrotron suppliers and increase the modularity, availability and performance of the system. In the present configuration one main HVPS (MHVPS) is feeding the cathode of 2 gyrotrons (instead of 12 as in the original configuration) [1]. The physical interfaces with the gyrotrons have been optimized, the power modulation frequency has increased from 1 to 5 kHz as well as the rating of the MHVPS, in a first phase from 90 A to 100 A, and finally from 100 A to 110 A, to fulfil the gyrotron requirements and allow the use of future gyrotrons with output power > 1 MW.

The F4E contract for the final design, procurement, installation and commissioning on ITER site of the EU part to the EC HVPS was awarded in December 2013. During the next 6 years, Ampegon AG will work to deliver 8 MHVPS units rated at 55 kV and 110 A, 16 body power supplies (BPS) establishing the maximum gyrotron beam voltage at 90 kV in combination with the MHVPS, and the dummy loads for the MHVPS and BPS testing. The PS system will be designed to regulate the instantaneous output gyrotron beam voltage within typically 1 % from the reference and shut down in less than 10 μs in case of faults or arcs. Other important parameters for the gyrotron operation are the overshooting (< 1%) and the ramp-up/down times especially during modulation at high frequency (up to 5 kHz).

The HVPS design will adopt a pulse step modulator (PSM) topology solution, which provides high efficiencies, low impact to the electrical network and very good performance [2]. The design and operation of the MHVPS and BPS are planned to be coordinated to improve the overall performance, so that one unit compensates for the voltage variation of the other. The final design of the EU HVPS is planned for the end of 2014, while the first delivery will occur about 2 years later, when the dedicated RF building of ITER will be ready for installations.

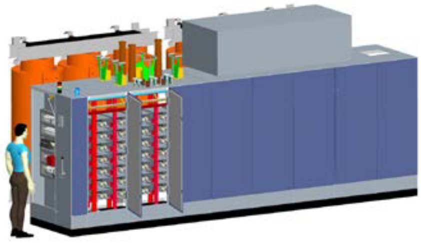

Figure 1. Schematic view of the MHVPS cabinet of power modules and transformers assembly

2.2 Gyrotrons

It is planned that 8 gyrotrons will be used for the start-up of the first plasma in ITER, 4 of them from Russia and 4 from Japan. The EU gyrotrons will be installed for the 2nd plasma operation phase, occurring about 3 years after the 1st plasma. The current EU gyrotron activities for ITER focus on the development of a 170 GHz, 1 MW, 3600 s $TE_{32,9}$-mode cylindrical-cavity gyrotron, the manufacturing design of which is chosen as close as possible to the design of the 140 GHz, 1 MW, 1800 s gyrotron for the W7-X Stellarator at IPP Greifswald [3,4]. The series production of the W7-X gyrotron at Thales Electron Devices (TED), France, is presently in the final phase (5 gyrotrons being accepted by IPP, 1 additional gyrotron is in final acceptance phase at IPP), and, therefore represents an excellent basis for the industrialisation of the gyrotrons for ITER [5]. In fact, it is well recognized by all gyrotron suppliers that due to the complexity of the tube manufacturing processes, caused by the high operating frequency (170 GHz), high output power (1 MW) and long pulse requirements (3600 s), the series production of the ITER gyrotrons will be particularly challenging to ensure the reliability of the performance.

The EU gyrotron development programme for ITER relies on a strong collaboration with the EU Fusion Labs associated in the EGYC Consortium (EPFL-CRPP/ Switzerland, KIT/ Germany, HELLAS/ Greece, IFP-CNR/ Italy), and the industrial partner TED/ France. Under this co-operative frame, the feasibility of the scientific and engineering design of the EU gyrotron has been confirmed by TED, who is in charge of the manufacturing design and the fabrication of the CW prototype. The delivery of the industrial 1 MW gyrotron prototype is planned for the 2nd half of 2015, in accordance to the F4E project plan for the technical validation of the EU gyrotron. The gyrotron development programme is complemented by the KIT activities for the manufacturing of a 1 MW short-pulse (ms) modular pre-prototype, the construction of which is planned to be as similar as possible to the industrial prototype. The short-pulse pre-prototype is presently in the manufacturing phase. The first RF test results are expected in last quarter of 2014.

The EU gyrotron development for ITER strongly benefits from the progress made in the modelling and design capabilities due to continuously strong research in the past years. Particular focus areas have been the improvement of electron beam quality, suppression of parasitic effects due to low frequency oscillations, the enhancement of the quality of the output RF beam, and the reduction of the peaks of heat load at the collector.

Nevertheless, the peak ohmic loading of the cavity inner walls, which is mainly scaling with $f^{5/2}$ where f is the frequency, will be high (2.2 kWcm^{-2} in nominal conditions). To mitigate this risk, dedicated mock-ups of the cooling concepts are going to be fabricated and tested at the beginning of 2015. Efforts are also being made to upgrade the gyrotron test beds at CRPP and KIT for the 1 MW gyrotron prototype and short pulse pre-prototype with advanced diagnostics and suitable microwave testing components.

In parallel to the gyrotron development, the activities for the conceptual and preliminary design of the gyrotron auxiliaries, including control, cooling manifold, supporting structures, and matching optics unit have started.

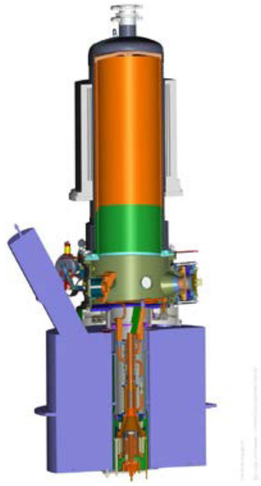

Figure 2. Schematic view of the EU 1MW gyrotron prototype

2.3 EC Plant level Control System

Due to the complexity of the ITER EC system and the numerous contributing parties, a ECPC is needed to implement the interfaces among the EC subsystems and with the ITER Central I&C, i.e. CODAC and the plasma control system (PCS) [6]. The ECPC coordinates the operation of the whole EC system, receiving requests and/or references from the PCS and providing commands to the EC subsystems to implement those requests, in a synchronized manner to setup the correct configuration. The most important role of the ECPC is to provide protection at plant level, when coordination among different subsystems is required. Most of the protection functions require switching the power supplies off in case of faults in other subsystems; it is worth noting that in some cases, e.g. arc protection, the time performance requirements are very demanding.

Given the number of subsystems and the high availability requirement of the EC system, it is envisaged to operate part of the EC system on the plasma while some of the subsystems are in testing or maintenance mode. The coherency among the subsystems in this complex operation is ensured by the ECPC. A possible use case is the conditioning of some gyrotrons during an ITER pulse.

The design and development of the ECPC have been divided in two main phases: in the first phase, all the functions needed for the acceptance tests and integration of the subsystems will be provided, together with the functionalities needed for the first plasma. In the second phase the interface with PCS will be fully implemented and some more complex algorithms will be included for plasma control and EC operation, e.g. neoclassical tearing mode (NTM) stabilization, automatic conditioning of gyrotrons. At each phase all the needed protection functions will be identified and implemented.

The conceptual design review of the plant controller was successfully completed in November 2013. The design process included the identification of the main control and protection functions starting from an analysis of the EC control in existing tokamaks (AUG, DIII-D, FTU, JT60, TCV), the specific adaptation to the projected operation of ITER, and the individual allocation of the various functions to the different controllers at plant and subsystem levels. The proposed I&C architecture for the overall EC plant is shown in the Fig.3.

Future activities include the finalization of the design in 2015 and the development of a preliminary version of the ECPS to be used for the factory acceptance tests of the various subsystems in 2016; the installation at the ITER site is envisaged in 2017 in time for the start of the on-site acceptance tests of the subsystems.

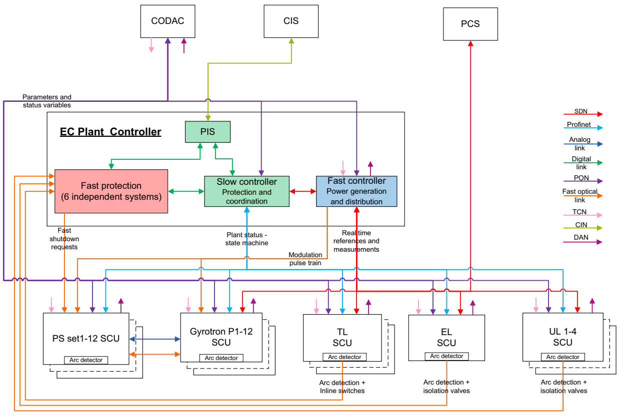

Figure 3. I&C architecture of the ECPC consisting of a slow controller implementing the slow control and protection functions, a fast controller for the control functions requiring a cycle time in the range of few milliseconds, and a fast protection controller to switch off the PS in few microseconds.

2.4 Upper Launchers

The four ITER EC ULs are plasma facing port plugs located in the upper ports of the ITER tokamak. The development of the UL final design is coordinated by F4E under an ITER task agreement. The engineering activities are performed by the European ECH Upper Launcher Consortium of Associations ECHUL-CA (KIT/ Germany, CNR/ Italy, CRPP/ Switzerland, Differ/ Netherlands, IPP and IPF/ Germany). Each launcher is made by a port plug housing all in vessel components and by an ex-vessel waveguide system (8 beam lines each) comprising waveguides, metre bends, isolation valve and diamond window.

The main purpose of the ULs is to drive local current with the aim to suppress NTMs. The UL is also designed to provide plasma breakdown and burn-through assist, current profile control, off-axis current drive in advanced scenarios and heating. Since the launcher is part of the ITER vacuum and first confinement boundary there are also several other key functions and requirements that the design is subjected to, including confinement of radioactive gas, neutron shielding and leak tightness under high-vacuum.

The main technological challenges for the EC UL include the ability to provide reliable and accurate steering of the mm-wave beam (front-steering mechanism assembly), an optical system with desired focusing and power handling (in-vessel mirror system, $\sim 4\ \mathrm{MWm^{-2}}$) and producing low stray radiation (analysis and testing). First wall elements have to be designed to allow beam propagation and sustain plasma loads ($0.35\ \mathrm{MWm^{-2}}$ steady state and flash thermal radiation loads during disruptions of $10\ \mathrm{MJm^{-2}s^{1/2}}$ for 10 ms), while the port plug structure is designed to be rigid to handle electromagnetic and seismic loads with minimal deflections (< 10 mm for 8 m length). Outside the vacuum boundary, the most challenging component is the high-power low-loss diamond window that provides the mm-wave transmission as well as the vacuum and safety function of primary confinement. In addition, a complete new design of the ex-vessel waveguide is in progress, since commercial off-the-shelf items (e.g. waveguide couplings) do not meet the stringent alignment requirements and are not suitable for ITER applications (compliance with vessel movements during baking, disruptions and seismic events).

These technical challenges have been either solved or under verification and qualification. However, new issues have arisen due to incomplete definition of technical requirements, changing interfaces, unclear safety qualification procedures and material requirements.

The current design strategy is based on a combination of design-by-analysis methods and prototypes testing, which is used for the qualification and verification of design aspects, demonstration of safety compliance and to prove the manufacturability of components. At present, five areas for prototyping testing and qualification are foreseen, to finalise and validate the design of the system: the microwave components (couplings, mirrors, isolation valve, etc.), diamond window assembly, port plug structure with blanket shield module, steering mirror assembly and mock-ups for diagnostics and ancillaries.

The complexity of the design, analysis and testing activities is managed following a formal system engineering approach. In-depth analysis and review is performed between ITER and F4E of the technical requirements and documentation for the launcher design, while considering the entire life-cycle of the system. For example, the load specifications are being defined not only considering the operational load conditions, but including also the loads associated to other phases of the life-cycle, such as testing, transport, manufacturing, installation, commissioning and maintenance. Dedicated databases and procedures have been developed to support the execution, review and archive of engineering analysis involving large amount of models and data that, particularly in case of components providing an important nuclear safety function (SIC), have to comply with very strict quality requirements for traceability and verification. The frequent changes to the system interfaces, both in-vessel and ex-vessel, have required strengthening of the control and management of the system configuration. This includes detailed reviews of the UL space allocation models, interface control documents and design environment, which are being performed in close collaboration with the ITER EC team.

The code and standards strategy for the design and fabrication of the UL have been defined based on comparative assessments between the available industrial codes (ASME, RCC-MR, EN standards, etc.) and taking into account the lessons learnt from the manufacturing and qualification of other ITER systems. The established strategy involves the use of non-nuclear codes (i.e. ASME VIII Div.2) for the design of the UL components that are not part of the first confinement system, to reduce costs and technical complexity for manufacturing and engineering validation. The SIC components are designed following the rules of ASME III. The rules from industrial codes and standards are then complemented with ITER-specific requirements associated to quality, vacuum and nuclear aspects. When industrial codes for nuclear use are not available (such as for the diamond window) an extensive prototype and qualification programme is established aimed at proof of design and establishment of a quality process for the series production.

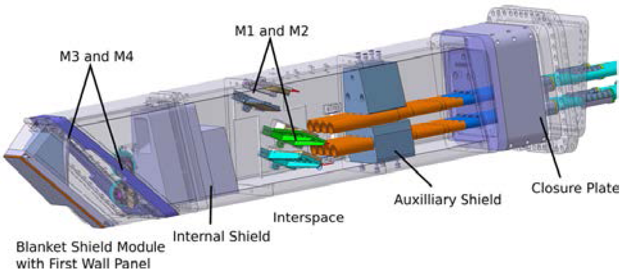

Figure 4. Schematic view of the port plug structure and in-vessel components

3 Activities for the optimisation of the EC system

Although the main technical specifications of the various EC subsystems are already frozen and the subsystems are progressing towards the final design status, there is still room for some optimisations, in particular regarding interfaces, procurement of critical common components and integration [7]. Running activities on this front are the assessment of the EC grounding network, common qualification programs for diamond window procurements, FMEA of the EC system, and the physics study aiming at assessing the level of EC power required for the various heating and current drive application on ITER ranging from initial break down, ramp-up assist, MHD control, current profile tailoring, through to the end of the pulse. The latter analysis will then be coupled with the ECPC design and interface with PCS for an optimized and coherent EC plant. In addition, F4E has agreed to embark on an integrated ECE system coupled with the launchers, which offers a line of sight ECE viewing system for simplifying the feedback control for NTM and sawtooth control.

In general, the assessment of the optimal solution is complex, since each sub-system is strongly impacted by the design and performance of the others, which, in turn, may be under the responsibility of another Party. However, it is a great opportunity to enhance the overall performance in the light of the recent technology developments. We take in the following, as an example, the IO physics requirement to modulate the EC power for NTM stabilisation and the optimization of the launcher steering angles for improved EC access.

3.1 EC power modulation requirements

It is well known that NTM instabilities in ITER may lead to an increase of the radial transport in rotating magnetic islands, causing a significant degradation of the confinement and reduction of the core temperature and plasma pressure. In addition, they can ultimately result in plasma disruptions. The NTM instabilities could therefore reduce the performance of the ITER plasma scenarios and need to be actively controlled. The strategy selected in ITER to control NTMs is to drive off-axis EC co-current to replace the missing bootstrap current in the magnetic islands [8]. This method, although challenging for the alignment of the ECCD with the magnetic island surface by the use of appropriate control schemes and actuators, has been shown to be successful in present day tokamak experiments (ASDEX-Upgrade, DIII-D, JT-60U, TCV). It has been predicted and experimentally observed that the efficiency of the stabilisation can be increased when the ECCD is applied to the O-point of the island, which is rotating poloidally. This requires modulating the EC injected power in phase with the island by implementing a feedback plasma control and acting on the EC power supplies that provide the voltage and current to the gyrotron electrodes.

Various options exist to achieve this functionality with the EC system:

- Switching ON/OFF both the cathode and body voltage, sufficiently fast (especially for the 5 kHz regime), typically in less than 50 µs, and limiting the voltage overshooting. This solution increases the complexity of the HVPS (and their dissipation losses).
- Maintaining the cathode voltage constant and modulating the body voltage from nominal to a value reducing at least 50 % the gyrotron output power. While this option could be acceptable for the plasma stabilisation requirements and relaxes the design of the HVPS, it introduces an additional heat load (of typically about 25 %) on the gyrotron collector which could endanger its lifetime.
- Similarly as in the previous, the body voltage could be maintained constant while partially modulating the cathode voltage. This modulation regime would allow achieving power modulation depth of 50 % or more and keeping the average power deposition on the collector to levels similar to continuous operation. This regime is subject to experimental validation to assess the gyrotron operational limits under which there are no reflected electrons influencing the interactions.
- For the triode-type gyrotrons provided by JA-DA the possibility exists to switch only the anode voltage and keep the MHVPS and BPS ON.
- The individual modulation frequency of the HVPS units could decrease if the gyrotrons are switched in groups in a synchronized way to achieve the required overall variation of the total output power. The complexity in this case is partially shifted to the EC controllers.

The detailed analysis done by F4E and IO involving industry for diode-type gyrotrons concluded that the option of switching ON/OFF both MHVPS and BPS was the most reliable and efficient solution for the EC system.

3.2 EC power deposition accessibility

The uniqueness of an EC system as compared to other H&CD systems is that the power deposition can be extremely localized and that the location can be steered using external actuators (steering mirrors). Application of localized H&CD is useful across nearly the entire plasma cross section, for example: on axis heating for impurity control, mid radius for current profile tailoring and sawtooth control, to the outer half of the plasma for NTM control.

The design of the upper and equatorial launchers has been optimized in a 3 step process, with the objective to increase power deposition accessibility across nearly the entire plasma cross section. Prior to 2006, the EL had limited access over the range of $\sim 0.2 < \rho < 0.42$, while the UL limited to $\sim 0.5 < \rho < 0.82$, resulting in ‘no access’ zones in the plasma center and at mid radius. EU initiated a series of proposed modifications to both the EL (adding small toroidal tilt angles) for more central access, and spread out the steering range of the UL upper (USM) and lower (LSM) steering mirrors for access at mid radius [9,10]. The IO initiated these changes in 2010 and achieved the access as shown (blue line) in Figure 5.

More recently, IO, EU and JA-DA have studied changing the EL from toroidally steering the beams to a poloidal steering. Poloidal steering can provide access out to $\rho < 0.6$, and with ~ 025° toroidal injection angle, the net EC driven current would more than double in the range of $\sim 0.42 < \rho < 0.6$ [11]. The poloidal steering EL was implemented in the design basis in 2014, and filled in the ‘hole’ of EC access at mid radius, as shown in Figure 5 (green line).

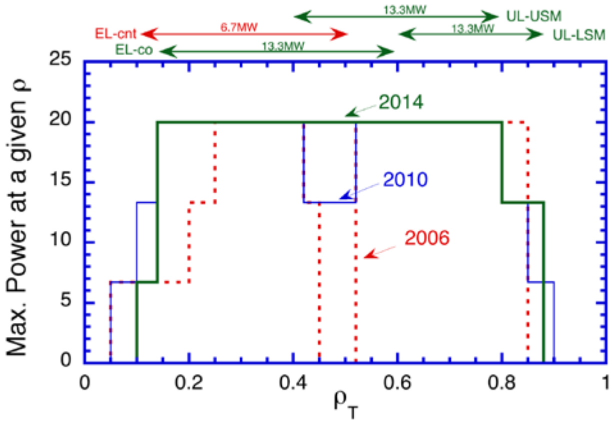

Figure 5. Progress increasing the EC power access by improving the UL and EL designs of 2006 (red), 2010 (blue) and 2014 (green). Above the plot is the steering range of the co and cnt-ECCD EL beams and the UL steering mirrors.

4 Summary

The EU contribution covers parts of the EC system from nearly the entire 'plug' to 'plasma' path, with the exception of the transmission lines (fully supplied by USIPO). EU provides roughly 67% of the HVPS, 25% of the sources, all waveguides from window to launchers, all ULs and the ECPC. The EC subsystems are progressing towards the final design status in pace with the first plasma requirements, with the first procurement (HVPS) recently initiated. The active involvement of IO during the implementation of the F4E activities and contracts has been shown to be crucial for a smooth integration of the EC subsystems.

The wide contribution from the EU has helped the IO in optimizing the overall design and functionality of the EC system and reducing the overall risk and complexity. The EU has performed background EC H&CD analysis, which has helped to understand the potential capabilities of the EC plant, that have then guided design changes leading up to a coherent system design as illustrated herein.

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