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Topic: TEC-HCD - Heating & Current Drive

Qualification of the European gyrotrons and power supplies of the Electron Cyclotron Heating and Current Drive system of ITER

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1. Introduction

The Electron Cyclotron Heating and Current Drive (ECH&CD) system is emerging as the major plasma heating system of present and future magnetic confinement fusion devices. This is attributed to its effective coupling into the plasma, the limited impact on the neutronics shielding of future reactors, the modularity of the system that maximizes the reliability and availability, and its versability in providing multiple essential plasma functions, such as the control of instabilities occurring in high performance plasmas. In ITER, the ECH&CD system will inject 40 MW to 67 MW of electromagnetic power into the plasma at pulses lengths of typically 500 s at an operating frequency of 170 GHz, playing a crucial role in all plasma phase scenarios to achieve ITER's objectives.

The millimeter waves are generated in gyrotrons connected to High Voltage (HV) power supplies, constituting the ECH power generation system, which employs technologies that are at an advanced readiness level for plant operation. Fusion for Energy (F4E), responsible for the European contribution to ITER, is tasked with procuring 8 out of the 12 High Voltage (HV) Power Supplies and 6 out of the 24 gyrotrons of the ITER ECH original baseline.

2. EC Power Supplies

2.1 Description

The EC High Voltage Power Supplies (HVPS) procured by EU to ITER comprise 8 HV main power supply units, each capable of delivering up to 55 kV DC regulated voltage and up to 110 A current, and 16 units dedicated to modulating the body voltage, providing up to 35 kV DC, thereby establishing the total gyrotron acceleration beam voltage (up to 90 kV DC). The main HV power supply feeds two gyrotron cathodes in parallel. When established, the cathode voltage of the gyrotron works in the temperature limited regime where the beam current is linearly dependent on the voltage, as a quasi-resistive load [8] in the range of 1 kΩ. The body power supply feeds instead the gyrotron body, which is an almost purely capacitive load (~3 nF), delivering ~100 mA in steady state and few Amps when doing fast (~50 μs) ON/ OFF modulation. Dummy loads are provided for the acceptance tests of the power supply system.

The selected design concept of the EU power supplies represents an advancement of the solid-state Pulse Step Modulator (PSM) technology, which provides high efficiency and compact layouts. The design incorporates specialized multi-winding transformers, which are powered by the 22 kV and 400 V AC electrical distribution system of ITER for control and instrumentation part. The secondary windings feed low-power modules with rectifiers and switches connected in series (92 power modules for the main HVPS and 28 power modules for the body HVPS, respectively). In addition, some of the switching modules of the main HV power supply allow pulling the current from the load, thus strongly reducing the energy delivered to the gyrotrons in case of fast shutdown request (e.g., gyrotron arcs). The system incorporates a soft start system to direct the inrush current of the transformer to resistors when switching on. Moreover, the body HV power supply includes an additional DC/DC converter in the modules to ensure an equal energy flow.

Considering that the availability of the ECH&CD systems is a key factor for the success of the ITER scientific program, the design adopts solutions maximizing the reliability of the system, paying special attention to the protection and safety functions and EMC compatibility. Each PS unit is an independent subsystem and therefore equipped with the complete control infrastructure for standalone and remote operation from the ITER higher level control layers as well.

2.2 Qualification and test results

The HVPS design which was developed by AMPEGON Power Electronics AG was optimized and verified by detailed simulations of all possible operating configurations with special focus on transients. Prototyping tests were performed on the power modules of the main and body HV power supplies to characterize the electrical behaviour and performance on instrumentation and control, dynamics (e.g. reaction times) and thermal dissipation. After completion of the manufacturing and assembly of the 1st unit, type factory verification tests were carried out showing: (i) excellent functional performance results on voltage stability (achieving < 500 V peak-to-peak and ± 0.25% accuracy), which allows to operate gyrotrons closer to the mode stability limit thus maximizing RF power and efficiency; (ii) great dynamics (such as the 5 kHz ON/ OFF voltage modulation as required for neoclassical tearing mode (NTM) plasma stabilization); and (iii) very low-energy dissipation to gyrotrons in case of fast shutdowns (< 1 Joule dissipated in < 10 μs). Exceeding the stringent technical specifications is highly beneficial for the gyrotrons, as well as for the power availability and reliability of the EC system.

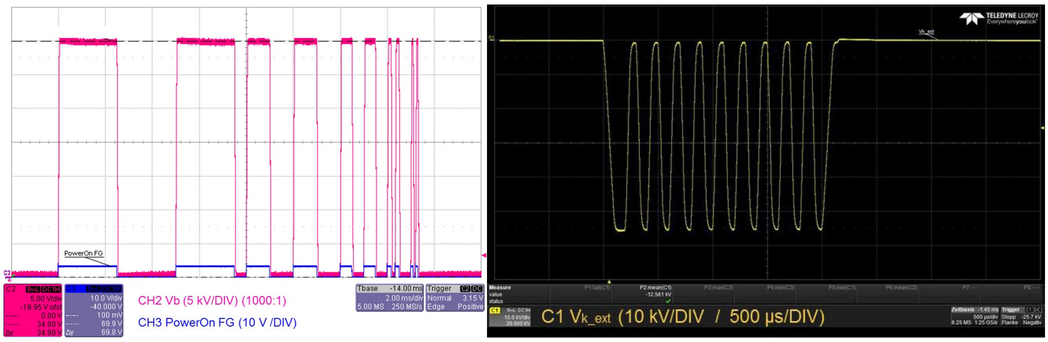

Figure 1: Measurement of the output voltage in the nominal operating point of the body HV power supply at 35 kV nominal output voltage and different modulation frequencies, on the left-hand side, and of the main HV power supply at 55 kV nominal output voltage, on the right-hand side, at the modulation frequency of 5 kHz supplying the dummy loads and relevant HV cable connections during the factory acceptance tests. Ramp-up/down times are of ~50µs.

2.3 Site installation

The main and body HV power supplies have been installed in the levels 1 and 2, respectively, of the RF building of ITER, below the gyrotrons that are currently being installed in the level 3.

Figure 2: The European EC main HV power supplies installed in the level 1 of the ITER RF building occupying an area of around 16 x 20 m.

Installation solutions were selected to protect personnel and equipment from electrical hazards, such as contact, flashovers, earthing issues, overcurrent, overvoltage, fire, and high temperatures. Nevertheless, obtaining regulatory approval has been slow and challenging due to the absence of specific standards for ECH&CD system construction and EC power supply assembly. Additionally, compliance with the French NF C13-200 standard - meant for power substations and differing from international PSM-based HV power supply standards - has further complicated the process.

The installation solutions are designed to mitigate EMC issues that affect plant reliability, including interference from the PSM switching concept of the power supply system, stray currents generated when two gyrotrons use a single main HV power supply, and gyrotron arcing events [1]. As a result, careful selection of cabling selection and routing, along with system connections to a common bonding network - a 5 x 5 m grounding mesh embedded within the ITER RF building's concrete floors and all metallic structures – are crucial. Furthermore, in compliance with the French safety electrical standards, each medium voltage (MV) AC component — such as switchgears, transformers, and enclosures — is connected to an earthing bus located within level 1. This bus provides a low-impedance path to a buried earth electrode that surrounds the building, allowing current to return to the upstream MV AC substation. This configuration maintains ground potential within acceptable limits in the event of a short-circuit to ground.

2.4 Commissioning

The commissioning of the 1st unit of the European contribution to the ECH&CD HV power supply system is completed, and final site acceptance tests are currently underway.

The commissioning sequence began with the assembly and electrical inspections, and the low-voltage (LV) commissioning, which serves as a foundational step in verifying the correct operation of the system's basic electrical and control circuits. The next stage involved the specific and thorough verification of the PILZ safety certified control system together with the mechanical keys interlocking strategy. During this phase, the following functions are verified for all possible combinations of signal values: green lights and state machine sequence, door locks and contactors, grounding switch lock, LV and MV breakers. Finally, before energizing the system with HV, withstand tests were successfully carried out on the body and main HV power supplies to verify the HV insulation of the system on AC (as per applicable standards) and DC (at a rated voltage of 1.7 times the nominal voltage for 1 minute, as per the specifications, reduced to 80 % testing voltage when repeated). The following parts were tested (i) MV AC cables connecting the switchgears to the soft start of the main HV power supply, (ii) the soft start system, (iii) the HV DC output filter and output receptacles, and (iv) the stack of power modules connected to the secondaries of the multi-winding transformers. The MV switchgear was also stand-alone commissioned and energized to the 22 kV incoming network.

The HV commissioning encompasses the verification of the full functionality of the system in all the possible operating modes and conditions and the fine tuning of the PSM control to optimize the output performance. The functional tests of the system on the dummy loads aim at verifying the specifications and confirm the excellent factory acceptance test results in its final site configuration.

3. Gyrotrons

3.1 Description

The ECH&CD gyrotron systems, including the vacuum tube, the super-conducting magnet and various auxiliaries, are each capable of delivering 1 MW at the main operating frequency of 170 GHz Continuous Wave (CW) for plasma heating and current drive. The F4E procurement package covers the Final Design Review (FDR), manufacturing, assembly, factory testing, and, at ITER site, installation, commissioning and acceptance testing of the 6 EU gyrotrons for ITER. The F4E procurement package also includes the design, delivery, installation and commissioning at ITER site of the EC gyrotrons control system.

The design of the EU gyrotron for ITER was developed by the EGYC Consortium (KIT, SPC, CNR, HELLAS) and the EU manufacturing industry (Thales), under the coordination of F4E, taking advantage of the successful manufacturing of industrial 1 MW 140 GHz CW gyrotrons by Thales for the Wendelstein 7-X [2]. A collaboration between F4E and DTT (Divertor Tokamak Test machine in Frascati, Italy) has also been crucial for the EU gyrotron qualification. In particular, two gyrotrons have been manufactured and tested to demonstrate qualification for the ITER and DTT projects: the EU gyrotron prototype (model TH1509U) and the DTT pre-series unit (model TH1509UA).

3.2 Design

The industrial gyrotron prototype TH1509U is based on the THALES diode-type magnetron injection gun and single-stage depressed collector configuration concept that has a strong reliability proven during several years of operation [9]. The unit relies on an interaction cavity operating in the $TE_{32,9}$ mode with an axial magnetic field of B_c = 6.77 T to provide 1 MW CW output power in the form of a Gaussian TEM_{00} beam, which is generated by a quasi-optical system including a launcher antenna, phase correcting mirrors and a CVD diamond window [10]. The industrial gyrotron design was optimized during several years through a step-by-step approach by integrating and validating last generation subassemblies, including the cathode structure, the high-voltage feedthroughs with the strengthening of body insulation as well as the beam tunnel and the interaction cavity with particular care to maximize the power output while suppressing the excitation of parasitic modes. The cooling circuits were consequently upgraded to manage the higher power load attainable and a dedicated filament control system was introduced to improve the power output stability of the gyrotron.

Additional upgrades focused on gyrotron assembly manufacturing files and production methods. All these operations enabled THALES and EGYC, in collaboration with F4E, to finalize the European industrial gyrotron designed for the ITER and DTT 170 GHz ECH&CD systems. The developments concern not only performance and reliability but also usability, maintainability, manufacturability and the respect of international standards and regulations.

3.3 Qualification

The gyrotron design was validated in a dedicated experimental campaign performed on the Short-Pulse (SP) modular gyrotron at Karlsruhe Institute of Technology (KIT). Extensive measurements were performed for pulse durations up to 5 ms using different magnetic field profiles. The electron beam radius at the cavity was varied between 9.35 mm and 9.65 mm and the angle of the magnetic field at the emitter ranged from - 3° to + 2°, in order to investigate different electron beam parameters, yielding velocity pitch factors ranging from 1 to 1.6 [11]. The tube was operated with a beam voltage of up to ~80.5 kV and delivered 1.6 MW output power at the window with 66 A of beam current, with total absence of parasitic modes. An RF efficiency of 33 % without voltage collector depression and 50 % of total efficiency with single stage collector depression were demonstrated in short pulses.

Two industrial CW gyrotrons, the TH1509U prototype for ITER and the TH1509UA as the first series tube for DTT, have been produced by Thales [3]. The design of the first series tube for DTT builds upon the prototype, incorporating adjustments to enlarge the operating domain without parasitic oscillations during long pulse operation. Factory tests of both tubes revealed full compliance to the vacuum level, hydraulic characteristics, heating filament impedance and high-voltage standoff requirements. The RF CW power testing was performed at the KIT [4] and SPC [5], [6] facilities.

Figure 3: The TH1509U gyrotron successfully preliminary tested in Thales, Vélizy, France [3].

Both TH1509U and TH1509UA gyrotrons have showed a power level of > 1 MW at the gyrotron output window with an output power stability better than 5% in the tests at the SPC Lausanne. Efficiency exceeded 40 % during five consecutive 100 s pulses, with a beam voltage of ~80 kV (including ~25 kV of body depression voltage) and a beam current of 47.5 A, all without parasitic modes. Pulses of 1000 s at the 1 MW power level were also demonstrated. Equally important, the gyrotron tubes provide a very stable performance, with excellent stability on critical parameters such as the frequency, vacuum level, beam current, calorimetry measurements, temperatures on the inner parts of the gyrotron, mode purity, and absence of mode switch at long pulses. Moreover, the EU gyrotron has demonstrated repeatability and reliability with successful consecutive pulses, when operated with ITER-like power supplies and controlled via an ITER-type Plant Control system [7] ensuring safe gyrotron operation as well as correct monitoring of the gyrotron diagnostics (e.g., frequency shift, mode purity, parasitic oscillations).

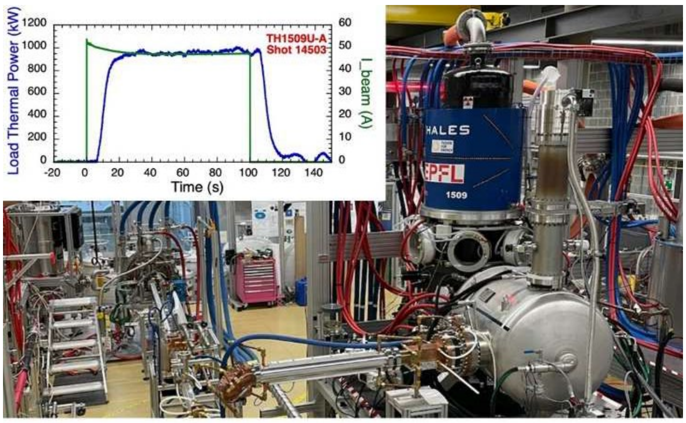

Figure 4: TH1509U under test at SPC with plot of beam current and calorimetry power at the dummy load over time [3].

3.4 Gyrotron next steps

The EU 170 GHz gyrotron qualifies for both ITER and DTT and has the potential for even higher power performance that has not been explored in long pulses yet on the TH1509UA gyrotron. However, the total efficiency currently does not meet the ITER target of 50 %, and certain optimizations have been identified for implementation in the next evolution. The series production of the six EU gyrotrons for ITER will start after the Final Design Review currently being finalized, with deliveries in the period 2027-2029.

4. Conclusions

The EU HV power supplies and gyrotrons for the ECH&CD system of ITER have been successfully qualified. The HV power supply system has been manufactured, delivered and installed in ITER, and the first commissioned unit is currently undergoing final acceptance testing to verify its performance as demonstrated during type factory tests that exceeded specifications. Design solutions and grounding have been optimized to ensure exceptional voltage stability and dynamic response, which are essential for gyrotron protection and for maximizing the power availability of the ECH&CD system.

In accordance with the agreed schedule for ITER, the European gyrotrons are undergoing final design review to ensure compatibility with ITER interfaces and will be delivered to ITER in the period 2027-2029. The European 170 GHz gyrotron design has been successfully qualified for ITER and DTT, as demonstrated by tests on the KIT short pulse modular gyrotron, the industrial CW prototype, and the first series unit for DTT. A notable feature of the EU design is its reliability within the MW power range, maintaining strong stability across critical gyrotron parameters and allowing for possible capacity enhancements. While the existing gyrotron efficiency satisfies the needs of DTT and original baseline of ITER, further optimizations are planned for the version of the tube to achieve 50 % efficiency.

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5. References

[1] U. Siravo *et al.*, EMC and earthing concept of the ITER EC-system, Fusion Engineering and Design 193, Aug. 23, 113719

[2] H. P. Laqua *et al.*, The ECRH-Power Upgrade at the Wendelstein 7-X Stellarator, EPJ Web of Conferences (EC21) 277, 04003 (2023) doi: 10.1051/epjconf/202327704003

[3] A. Leggieri *et al.*, Industrial Qualification of the THALES TH1509U European 170 GHz 1 MW CW Gyrotron, 2024 Joint International Vacuum Electronics Conference and International Vacuum Electron Sources Conference (IVEC + IVESC). IEEE,

pp. 1–2, Apr. 23, 2024. doi: 10.1109/ivecivesc60838.2024.10694857
[4] T. Rzesnicki *et al*., Experimental Testing of the European TH1509U 170-GHz 1-MW CW Industrial Gyrotron—Long Pulse Operation, 2022 IEEE Electron Device Letters, vol. 43, no. 4. Institute of Electrical and Electronics Engineers (IEEE), pp. 623–626, Apr. 2022. doi: 10.1109/led.2022.3152184
[5] T.P. Goodman *et al*., Tests and Qualification of the European 1 MW, 170 GHz CW Gyrotron in an ITER relevant configuration at SPC, 2022 47th International Conference on Infrared, Millimeter and Terahertz Waves (IRMMW-THz). IEEE, pp. 1–2, Aug. 28, 2022. doi: 10.1109/irmmw-thz50927.2022.9895782
[6] F. Braunmueller *et al*., Results on the 1 MW CW 170 GHz gyrotron TH1509UA for ITER and DTT at the FALCON test stand, EPJ Web of Conferences, vol. 313. EDP Sciences, p. 04005, 2024. doi: 10.1051/epjconf/202431304005
[7] G. Carannante *et al*., Status of the ITER ECRH&CD control system development, EPJ Web of Conferences, vol. 277. EDP Sciences, p. 04005, 2023. doi: 10.1051/epjconf/202327704005
[8] M. Kartikeyan *et al*, Gyrotrons: High-Power Microwave and Millimeter Wave Technology, Springer, 2004.
[9] A. Leggieri et al., THALES TH1507 140 GHz 1 MW CW Gyrotron for W7-X Stellarator, 44th IRMMW THz 2019, Paris.
[10] A. Leggieri *et al*., TH1509U European 170 GHz 1 MW CW Industrial Gyrotron Upgrade, 22nd IVEC, Monterey, 28-30 Apr 2021.
[11] T. Rzesnicki *et al*., Parasitic-Modes Free, High-Performance Operation of the European 1 MW, 170 GHz Short-Pulse Prototype Gyrotron for ITER, IRMMW-THz 2023, Montreal, 17-22 Sept 2023.